TOWARDS THE DESIGN OF SPORTS COMPRESSION GARMENTS WITH CONTROLLED PRESSURE

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Abstract

Sports compression garments (SCGs) are skin-tight, elastic garments that are designed to be smaller than the wearer's body to apply pressure to the underlying body. This is claimed to improve performance, shorten recovery and prevent injuries. The level of pressure applied by SCGs is affected by a complex interaction of body dimensions, garment characteristics and fabric properties. With most existing research on SCGs drawn from medical or sports science fields, studies frequently neglect considerations of users and the way SCGs behave on the body. Consequently, the SCG-body-relationship is not well understood and the pressures applied by commercial SCGs vary widely. This research set out to enhance theoretical and practical knowledge on the design of SCGs by defining a framework for the design of SCGs with controlled pressure. To achieve this, user experiences with SCGs were obtained through an online survey and wearer trials and the designs and pressure distributions of commercial SCGs were analysed. The research further assessed the feasibility of using the built-in pressure map of the commercial 3D CAD software Optitex PDS 11 to predict pressures applied by SCGs.

Findings from the online survey revealed that respondents were overwhelmingly satisfied with commercial SGCs and that they wore SCGs mainly for their recovery-enhancing rather than performance-enhancing properties. Wearer trials with 33 physically active females in SCGs were conducted to capture 3D scans of their bodies and measure the pressure applied by commercial SCGs. The wearer trials indicated that, despite high levels of user satisfaction identified by the online survey, compression levels varied widely across pressure measurement locations and across individuals. This suggests a strong perceptual effect of SCGs. It was concluded that variations in pressure levels were likely to be associated with variations in fit and fabric tension caused by deficiencies in the applied sizing system.

The commercial SCGs under investigation were deconstructed, re-engineered and virtually fitted to a set of remodelled body avatars of 15 wearer trial participants. Virtual pressure measurements were compared to in vivo measurements. Findings highlighted problems with the accurate simulation of technical garment properties. It was concluded that 3D CAD virtual fit technology is currently limited to the visual representation of garments for marketing and sales purposes, but is not useful for technical product development or pressure prediction.

The findings were synthesised and conceptual design principles and a user-centred design framework were defined leading to the development of a model that incorporates a design process, user needs and technical product requirements: the SCG Design Model. By applying a novel inductive interdisciplinary methodological approach, this work has provided a different perspective to the research on SCGs. This approach has created new knowledge and tools for the design of SCGs and opened up new areas of research. This research has the potential to improve SCGs by, on the one hand, enhancing the theoretical and empirical knowledge base, which is expected to lead to more holistic and better-informed research on SCGs and, on the other hand, facilitating the design of SCGs with controlled pressure in practice.

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Publications

I have published the following material in advance of my thesis and the publications have been bound in at the back of my thesis according to the Institutional Code of Practice and Research Degrees Regulations:

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List of Acronyms

2D	–	Two-dimensional
3D	–	Three-dimensional
ANE	–	Apparel needs expectation
BMI	–	Body mass index
BS	–	British Standard
CAD	–	Computer-aided design
CAM	–	Computer-aided manufacturing
CG	–	Compression garment
DOMS	–	Delayed onset muscle damage
ECE		European Colorfastness Establishment
EMG		Electromyography
FAST	–	Fabric Assurance by Simple Testing
FCD	–	Functional clothing design
FE	–	Finite element
FEA	–	Functional, expressive, aesthetic
FFIT	–	Female Figure Identification Technique
FTU		Fabric Testing Unit
ISO	–	International Organization for Standardization
KES-F	–	Kawabata Evaluation System for Fabrics
MCG	–	Medical compression garment
MCS	–	Medical compression stockings
MFI	–	Manchester Fashion Institute
MRI		Magnetic resonance image
NCP	–	Normal collision pressure
PDS	–	Pattern Design Software
PM	–	Pressure measurement
QFD	–	Quality Function Deployment
RBM	–	Refined body mesh
SCG	–	Sports compression garment
SD	–	Standard deviation
UoM		University of Manchester
WT	–	Wearer trial

1 INTRODUCTION AND BACKGROUND

1.1 Background to the Research

1.1.1 Sports Compression Garments

Sport has always been an important part of human society. It has established itself into an international phenomenon, which is showcased in some of the biggest international events. As a part of culture, sport reflects society and has developed as society developed (Jarvie, 2006). In today's fast-paced world of high-tech innovations athletes and trainers search for technological innovations to improve exercise performance and recovery, as discrepancies of performance among elite athletes in many competitive sports have become diminutively small (Senner et al., 2009).

In their search for new ways to improve human performance, two decades ago, inspired by the successful application of compression therapy in the medical sector since the 1950s, sports scientists discovered compression garments (CGs) as a relatively simple mechanical modality to be applied in sports (Perrey, 2008; Senner et al., 2009). Sportswear had long been made from elastic fabrics due to the improved comfort and fit that stretch fabrics offer (Voyce et al., 2005), but this led to the development of highly elastomeric sportswear designed to compress underlying tissues in an attempt to transfer the beneficial effects of medical compression garments (MCGs) to the sporting environment.

Sports compression garments (SCGs) are skin-tight, elastic garments that, unlike conventional clothing, are designed to be smaller than the dimensions of the wearer's body (usually 15-20%) (Liu and Little, 2009; Troynikov and Ashayeri, 2011). The negative fit ensures the application of pressure to the underlying body.

Compression pressure, in general, is a force applied to an area of body surface (Tyler, 2015; R. Liu et al., 2017) and is often referred to as interface pressure (Partsch, 2005). It is defined as (Tyler, 2015; R. Liu et al., 2017):

$$P = \frac{F}{A} \qquad \text{(Eq. 1)}$$

where P = pressure, F = force and A = area affected by the applied force.

In SCGs, compression pressure is the force of garment strain applied to the surface of the defined region on the wearer's body (Partsch, 2005), which hereafter is just referred to as pressure. As SCGs are smaller than the wearer's body and have a high elastane content, they are stretched during donning and wear by applying mechanical forces to the fabric, yarns and fibres (MacRae et al., 2016). The level of compression is affected by the interaction of the force of the garment stretch and curvature and tissue composition of the area affected by the force, i.e. the human body (Troynikov et al., 2013; MacRae et al., 2016).

Over the past two decades, the use of SCGs has become increasingly popular with athletes in the USA and Australia, and more recently also gained popularity in Europe (Senner et al., 2009). Initially, SCGs were only used by professional athletes in swimming and running, but in recent years SCGs have entered the mainstream market and are worn by elite and recreational athletes from all kinds of sporting disciplines. As a result, there is a wide variety of different SCG types available, ranging from socks and arm sleeves to tops, tights and whole-body suits (Textiles Intelligence Limited, 2014a).

According to Hill and Pedlar (2012), the purpose of wearing SCGs is to improve athletic performance and post-exercise recovery. It is critical that SCGs fit properly, acting like a second skin so that they apply the desired pressure levels to the targeted areas of the body, are comfortable and offer optimised moisture and thermal regulation (Liu and Little, 2009; Fu et al., 2013; Textiles Intelligence Limited, 2014a). SCG brands claim that SCGs enhance blood flow and stabilise the body's tissue and through this provide the following benefits (Perrey, 2008; Senner et al., 2009; MacRae et al., 2011; Fu et al., 2013; Textiles Intelligence Limited, 2014a):

- Increased venous return,
- Faster removal of waste products from the muscles,
- Improved oxygen inflow to muscles,
- Improved endurance,
- Improved strength,
- Decrease of muscle energy depletion caused by vibration,
- Reduced fatigue,
- Enhanced recovery,

- Improved proprioception,
- Altered kinematic parameters,
- Reduced risk of injury,
- Provision of a psychological lift.

However, evidence for these beneficial effects is largely anecdotal and findings are often controversial. It is difficult to prove any benefits of wearing SCGs, as the underlying mechanisms of compression are currently not understood.

1.1.2 Sportswear Market Overview

The overall sportswear market has grown strongly in recent years (+7.3% 2015-2016) backed by an increase in sports participation due to a trend for healthier lifestyles and increased quality of life (Rahulan et al., 2013), but also backed by the ‘athleisure’ fashion trend, a growing trend to wear sports clothing and footwear during non-sport, everyday activities (Mintel, 2015a, 2016a; Martschenko, 2017). Whilst the boundaries between sport and fashion are more blurred and influence each respective market (O’Sullivan et al., 2017), engineered performance sportswear is one of the fastest growing segments in the global clothing industry (Subic et al., 2016).

Sport England’s ‘This girl can’ campaign has driven women’s sports participation in recent years encouraging 1.6 million non-active women to take up exercising in its first year (2015-2016) (Mintel, 2016b; Sport England, 2016). Sportswear brands are trying to increase their market share by developing their women’s sportswear offering. As a result, there have been notable changes in the women’s sports sector with many brands (e.g. Adidas, Nike, Reebok) targeting women with their marketing campaigns (Mintel, 2016a). In line with this trend, many high street fashion brands (e.g. H&M, New Look) have started to sell sportswear ranges with brands such as Marks & Spencer even offering women’s compression tights. However, the brand’s marketing focus does not lie on performance enhancement, but rather on figure enhancement. As such, the brand calls their compression tights ‘sculpting gym leggings’ (Barton, 2017). Mintel (2016a) forecast further growth in the women’s sportswear market in the foreseeable future.

According to a Mintel (2015a) survey, the most important factors for purchasing sportswear are comfort, low price and durability with women favouring sportswear that is comfortable and the latest fashion. However, consumers are also interested in performance enhancing characteristics of their sports clothing with 19% of respondents stating that such characteristics are important when wearing sports clothing and footwear (Mintel, 2015a). Consumers are willing to pay more for performance characteristics that could facilitate them to gain a considerable competitive advantage in their sports pursuits (Özdil and Anand, 2014).

With running (15.0%), cycling (15.4%) and fitness classes (14.3%) being the most popular sports in the UK, there has been an increased focus on fitness (Mintel, 2016a, 2017b), which could explain the growing interest in SCGs by recreational athletes. An increase of 78% in sales has been reported for SCGs in the US from 2008 to 2010 with compression socks and arm and leg sleeve sales reporting the highest growth rate (+600% and +750% respectively) (Textiles Intelligence Limited, 2014a).

The latest available figures from 2012 show that the market share of SCGs in the US sportswear market was approximately 6% (Textiles Intelligence Limited, 2014a). Whilst this represents a relatively small proportion of the overall sportswear market, the SCG market is forecast to continue its growth in the foreseeable future as SCG brands expand their product range and branch out into other sports disciplines (Fiedler, 2015). According to Beliard et al. (2015), there are over 100 types of compression stockings designed for sports application commercially available, indicating the popularity and growing market share of SCGs. With a robust demand and a high rate of innovation, the SCG market is forecast to outperform other performance sportswear markets (Textiles Intelligence Limited, 2014a).

1.2 Rationale

This research project emerged from existing research at Manchester Metropolitan University. The previous research on SCGs demonstrated substantial variations in compression forces for mid-range-sized men’s compression tops clothing a mannequin (Allsop, 2012; Venkatraman et al., 2014). These findings highlighted the need to further investigate pressure levels and distribution applied by commercial SCGs across different sizes.

The existing research further explored the use of 3D CAD virtual fit technologies to predict pressures applied by the compression tops to body models. However, the study did neither numerically evaluate simulated pressures nor consider effects of different simulation settings. It concluded though that virtual fit could potentially be a promising tool to predict applied pressures in the design phase of SCGs.

These findings led to the initiation of this research project, which set out to find ways to design SCGs with comparable compression across sizes and individuals within each size category utilising emerging three-dimensional (3D) technologies, such as 3D body scanning and virtual fit.

1.3 Problem Statement

Current research has mainly focused on measuring the effects of SCGs on exercise performance and recovery. The beneficial effects of SCGs as ergogenic aids in sports are, however, yet to be proven. The many research studies do not offer convincing conclusions as study designs are fuzzy, results are mixed and the heterogeneity of the studies inhibits meaningful comparisons. There is an obvious lack of garment focus in existing studies on SCGs since the background of most researchers is in the sports science field. Systematic research that considers the complex relations between applied pressure and the wearers' body measurements, garment construction, fabric properties and the size of the garments is lacking. Hence, the SCG-body-relationship is currently not well understood. With studies showing variations of pressure levels across individuals, consumers cannot make informed purchase decisions.

The research problem highlights the need for research that creates a better understanding of the way SCGs behave on the wearer's body in order to identify methods to design SCGs with controlled pressure. It opens up several questions that need to be addressed by this study:

- What is the current state of research on SGCs?
- What impact do SCGs have on body physiology of athletes?
- What factors affect the design development of SCGs?
- Why do athletes wear SCGs?
- How do athletes use SCGs?

- What garment features are important to athletes?
- What properties do fabrics used for SCGs possess?
- How do fabric properties affect the level of applied pressure?
- What construction methods are used for SCGs?
- What grading practices are used for SCGs?
- How does sizing compare across different SCGs?
- How does fit affect the level of pressure applied by SCGs?
- How do seams affect the level of pressure applied by SCGs?
- How does the level of compression applied by SCGs vary across individuals?
- How does the level of compression vary across different sizes?
- How do body movements influence the level of pressure applied by SCGs?
- How can SCGs be designed in a way that ensures consistent pressure distribution across the range of sizes and individuals?

1.4 Aims of the Research

1.4.1 Overall Aim

The overall aim of this research is to enhance theoretical and practical knowledge on the design of SCGs under consideration of emerging 3D technologies to work towards the design of SCGs with controlled pressure.

1.4.2 Specific Research Aims

The specific aims for this study to achieve the overall aim developed from the research questions and were defined as follows:

1. To analyse the existing knowledge base related to SCGs with specific focus on applied pressure.
2. To identify users' wear behaviour, preferences and attitudes related to SCGs.
3. To analyse commercial women's SCGs with particular focus on design, materials, sizing and applied pressure.

4. To create an improved understanding of how pressures applied by SCGs behave in relation to body dimensions and shapes of female recreational athletes.
5. To evaluate the use of 3D CAD virtual fit technology as a tool to predict applied pressures in the design process of SCGs.
6. To define a design framework that improves the ability to design SCGs to pre-determined pressure specifications.

Aim 1 creates the fundamental building block of this research. The analysis of the theoretical knowledge base identifies problems with existing research and opportunities to enhance the knowledge base. This provides the rationale and focus of this study. With a user-centred design process in mind, it is essential to evaluate user experiences with SCGs (Aim 2). This knowledge could highlight additional problems and opportunities. The focus then shifts from the user to the product in Aim 3, where commercial women's SCGs are analysed. Aim 4 combines the user and the product in an effort to create a better understanding of the SCG-body-relationship. The focus then shifts to the design process and the potential use of virtual fit for pressure prediction for the design of SCGs. Finally, the insights from Aims 1 to 5 will be synthesised to define a design framework that facilitates the design of SCGs with controlled pressure (Aim 6).

1.4.3 Specific Motivation

The motivation of the research is to highlight the importance of garment characteristics and create a better understanding of how SCGs behave on the human body. It is hoped that new studies with improved reliability and validity will emerge through this. These future studies may lead to a better understanding of the underlying mechanisms of SCGs and whether or not they significantly improve performance and recovery.

Due to the restriction of female sports participation and a neglect of women-specific sportswear developments historically (refer 3.2.3), this study is motivated by the aspiration to support female athletes in performing their best. Most research on SCGs has been conducting on men's specific SCGs, even though the gender gap in sports participation is slowly narrowing (Mintel, 2017a).

1.5 Contributions to Knowledge

The described aims will enable this research to apply a holistic, interdisciplinary research approach with a threefold focus on SCGs as items of clothing, SCG users and the design process. The investigation will be the first study to bring together all aspects related to the technical design of SCGs and will create a knowledge base that links pressure, the human body and garment design.

The study advocates the importance of focusing on the SCG and its characteristics as well as the needs and perceptions of users. Both these aspects have been neglected by existing research. It further offers an innovative approach to the technical design of SCGs by exploring the integration of emerging 3D technolologies into the design process.

The findings will add to the current knowledge of SCGs by presenting a more garment- and user-focused outlook to the current research base, which is dominated by scientific studies in the sports science and medical fields. As such, this study offers a novel perspective on SCGs. It will enhance the knowledge base of SCGs and enrich future research across the variety of disciplines related to SCGs (e.g. sports sciences, medical sciences, technologies, clothing and textile technology).

The final output of this research will be a framework for the design development of SCGs that is underpinned by theoretical findings but practicable in the apparel industry. It will be the first framework guiding the design of SCGs.

The new knowledge emerging from this study will also have practical implications as it will allow brands to more efficiently design SCGs and therefore give consumers the opportunity to make informed purchase decisions.

1.6 Scope of the Study

The study focuses on the design development of SCGs, this is understood to be the technical design from concept to product, however, it does not include marketing, sales or bulk production. A technical designer’s perspective is followed. This means, for instance, that the design process would involve ‘fabric selection’ as a process stage, rather than ‘fabric manufacture’.

The investigation will involve elements of textile technology, sports science, clothing technology and simulation technologies that can be applied in product development. While textile technologies and sports science are crucial aspects as background to the study, the main thrust and new knowledge of the study will lie within the areas of clothing technology and the application of technologies in the product development of SCGs.

The scope of the study is delimited to the relationship of clothing design and applied pressure. The study attempts to facilitate the design of SCGs to desired specifications, but will not provide any guidance on required levels of pressure. These specifications will have to be determined by further research in collaboration with sports scientists.

The study focuses on whole-body cut-and-sew CGs for sports use; hence, many of the findings and the design framework to be developed will not be applicable for seamless SCGs or MCGs.

Athletics is one of the most popular sports in the UK with a vast growth rate over the past decade (Sport England, 2016). Athletics was, therefore, chosen as a focus of this study, with a special emphasis on running. The research concentrates on female users due to the higher fit complexity of the female body and recent growth in women-specific performance sportswear development (Mintel, 2015a).

1.7 Thesis Structure

The thesis is divided into eleven chapters as outlined in Figure 1.1. Chapters 2 and 3 build the literature review of the study. Chapter 2 critically analyses existing literature on the functionality of SCGs. It serves as an introduction to the functionality of CGs in the context of sport, highlighting its complexity and limitations of existing research. Chapter 3 determines the contributing factors to the design of SCGs. Due to the small number of publications on SCG-specific design literature, publications from other related fields are reviewed and considerations for the design of SCGs derived.

Chapter 4 lays out the research methodology applied in this study. It describes the research perspective and development of the methodological framework and research strategy of this work.

The empirical research of this study is summarised in Chapters 5 to 10. Chapter 5 presents the key findings drawn from the literature review in relation to this research study. Chapter 6 presents and discusses the findings from an online survey with SCG users, whilst Chapter 7 reports the findings from analyses of commercial SCGs. The findings from wearer trials with SCGs are presented and discussed in Chapter 8. Chapters 6 to 8 focus on the relationships between users and SCGs, respectively addressing Aims 2, 3 and 4 of this study. Chapter 9 focuses on the evaluation of virtual fit technology for pressure prediction in line with Aim 5. All study findings related to the design of SCGs are synthesised in Chapter 10 and a design framework, aimed at facilitating the design of SCGs with controlled pressure, is developed. The chapter, thus, fulfils Aim 6 of the research.

Finally, Chapter 11 provides conclusions and recommendations for future work.

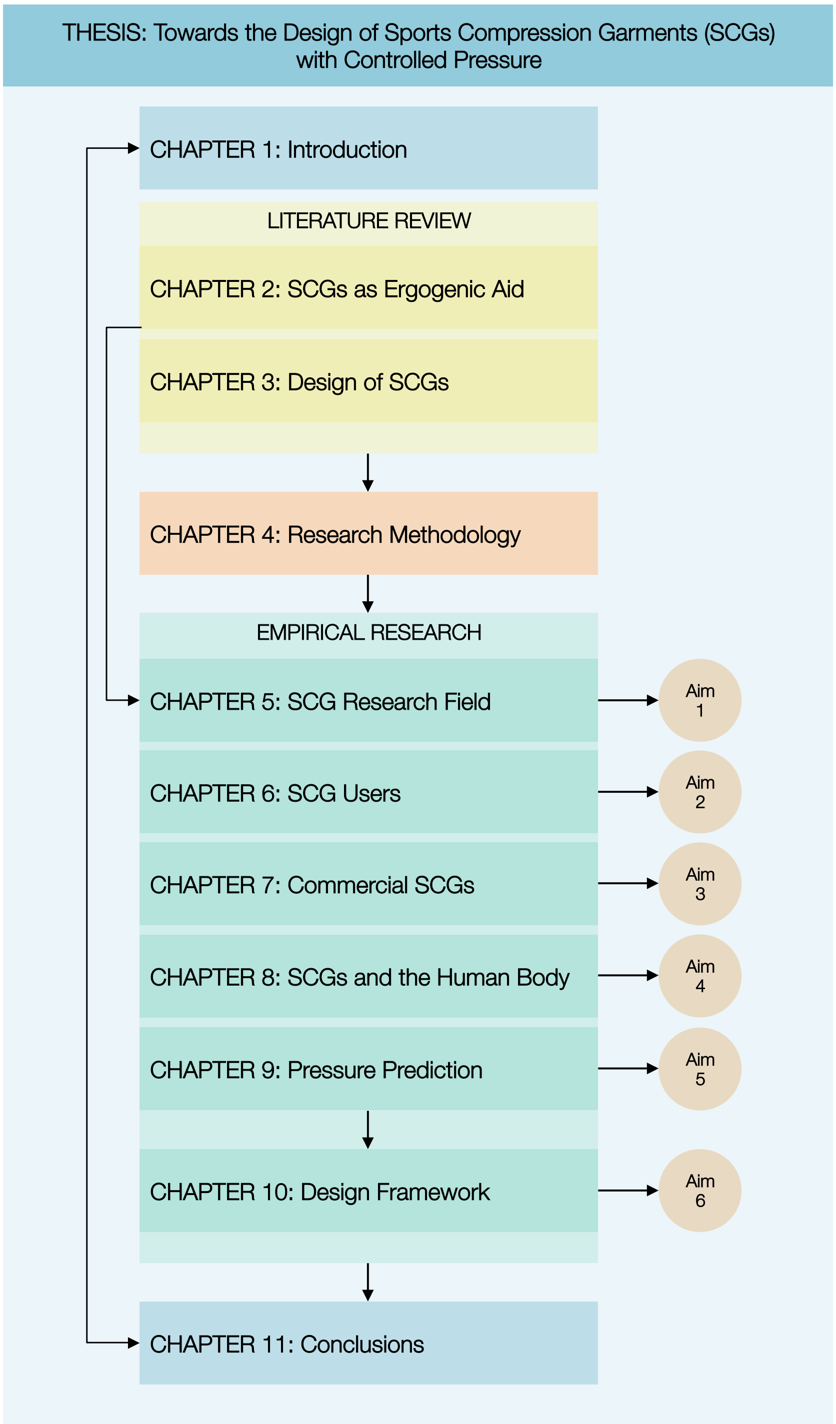


Figure 1.1: Thesis structure

2 SPORTS COMPRESSION GARMENTS AS ERGOGENIC AIDS

2.1 Chapter Introduction

This chapter reviews existing literature on sports compression garments (SCGs) from a sports perspective. It introduces the reader to the medical origin of compression garments (CGs) and the use of ergogenic aids in sport before providing an overview of the concept of compression pressure and ways of measuring it. The chapter then analyses existing studies evaluating the functionality of SCGs.

2.2 Medical Use of Compression Garments

CGs have been established in the medical sector as an effective and inexpensive means to treat venous dysfunctions since the 1950s (Buhs et al., 1999; Ramelet, 2002; Troynikov and Ashayeri, 2011; Rohan et al., 2013). Compression therapy is routinely applied to treat venous and lymphatic disorders, to prevent thrombosis and oedema in pregnancy, long and microgravity flights and post-surgery as well as to soften burn scars (Ramelet, 2002; Maton et al., 2006; Textiles Intelligence Limited, 2014a). Traditionally, compression has been applied by bandages, meaning its effectiveness was highly dependent on the technique and skills of the bandager (Moffatt, 2008). Today, compression therapy is mainly provided by Medical Compression Stockings (MCS) in the treatment of venous disorders and thrombosis prevention or custom-made medical compression garments (MCGs) for the treatment of burn scars.

MCS exist in a variety of lengths from socks to thigh-length stockings and tights, depending on the wearer's condition and tolerance. Advances in textile fibres, such as microfibers, have considerably improved the comfort of today’s MCS (Ramelet, 2002). With a growing occurrence of venous disorders caused by increased lifestyle-related diseases, such as diabetes, and an ageing population, the MCS market has high growth potential (Textiles Intelligence Limited, 2014a). MCS generally apply graduated compression with pressure levels gradually reducing from the ankle to the calf and thigh (Figure 2.1-a). This pressure gradient is believed to promote blood flow towards the heart (British Standards Institution, 1985; Linnit and Davies, 2007). However, some research (Mosti and Partsch, 2011, 2012, 2014) has shown better results for venous calf pump function with progressive pressure patterns (Figure 2.1-b).

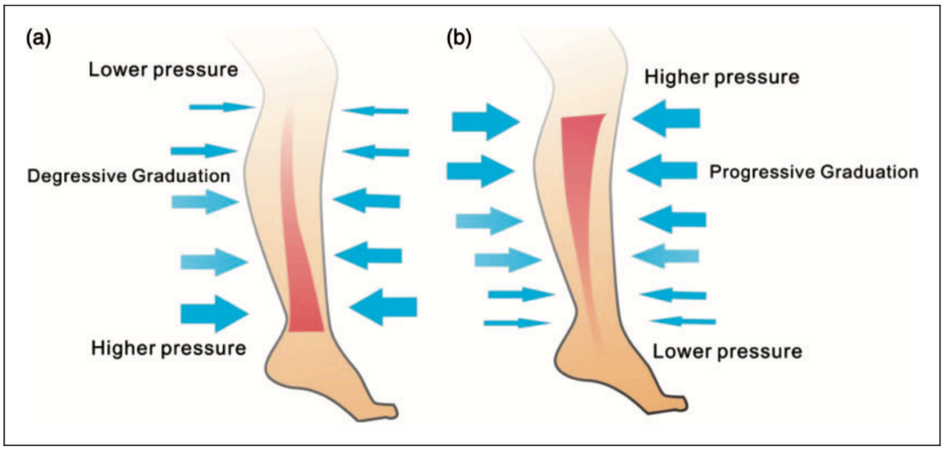


Figure 2.1: Two types of pressure profiles: a) degressive gradual compression; b) progressive gradual compression (R. Liu et al., 2017:7)

Ibegbuna and colleagues (2003) highlighted that any beneficial effects of MCS can only be achieved with correctly fitted garments. Apart from affecting pressure application, incorrect fit can also cause discomfort, which is one of the main reasons for lack of patient adherence to compression treatment (Feist et al., 2011; Miller, 2011). Ramelet (2002) further highlighted the need to replace MCS every four to six months due to reduction in pressure levels over time caused by repeated wear and laundering.

MCGs for the treatment of hypertrophic scars are generally custom-made by specialist manufacturers or by hospital staff and can take various shapes depending on the scarred body part (Ng, 1995; Macintyre, 2007).

The pressure unit millimetres of mercury (mmHg with 1 mmHg = 133.322 Pascal) is commonly used to describe the dosage of pressure applied by MCGs (R. Liu et al., 2017). For MCS only the pressure at the ankle at rest is generally reported (Linnit and Davies, 2007). The required amount of pressure depends on the severity of the symptoms and the patient's tolerance and is divided into different classes of compression intensity (Ramelet, 2002). There are no global standards and a European standard (ENV 12718) only exists in draft form (British Standards Institution, 2001), leading to variations in norms for compression therapy internationally (R. Liu et al., 2017). The most prominent pressure standards are listed in Table 2.1.

Table 2.1: Different standards classifying compression levels of MCS (Lymed, 2018)

Compression class	EU pre-standard	British standard	French standard	German standard	US standard
A – very mild	10-14	-	-	-	-
I - mild	15-21	14-17	10-15	18-21	15-20
II - moderate	23-32	18-24	15-20	23-32	20-30
III - strong	34-46	25-35	20-36	34-46	30-40
IV – very strong	>49	-	>36	>49	-

All pressure values in mmHg

Even though there has been a wealth of research on MCS over the past three decades, it is not unequivocally clear what the mechanisms behind compression therapy are (Rohan et al., 2013). However, it is widely believed that the pressure applied by MCS increases the pressure in the underlying tissue and consequently reduces the pressure difference between the inner and outer venous walls, called transmural pressure. As a result, the cross-section of the vein is reduced, creating a pressure gradient, which increases venous velocity (Spence and Cahall, 1996; Maton et al., 2006; Textiles Intelligence Limited, 2014a). In other words, MCS compress tissue, which in turn compresses underlying veins; as body fluids cannot be compressed, they are shifted in the vascular system resulting in increased blood flow (Tamoue and Ehrmann, 2017). However, some researchers, like Spence and Cahall (1996), are of the opinion that MCS are only affecting superficial veins and do not affect deep vein haemodynamics. Others (Buhs et al., 1999) suggest that MCS have no effect on haemodynamics, but rather have a direct anatomical effect. MCS are believed to improve muscle contraction by providing a firm wall for the contracting muscle to push against (British Standards Institution, 1985; Ibegbuna et al., 2003). In the treatment of burn scars, compression therapy is understood to accelerate the natural remodelling process of the skin resulting in flatter and softer scars (Sawada, 1993).

Even though SCGs developed from MCGs, they differ in appearance and level of pressure applied. Their appearance is based on general sportswear design in terms of style and colour. SCGs can be produced by conventional cut-and-sew methods or can be knitted seamlessly. Pressure levels of SCGs tend to be lower than the pressures elicited by MCS and pressure profiles are often zoned, applying varying levels of pressure to different muscle groups. Next to the apparent reason that healthy individuals do not require as much of a boost in blood circulation, another reason for the higher levels of pressure in MCS could be that the pressure applied by MCS must often be transmitted through several centimetres of swollen and excess tissue, which reduces the compression effect (Buhs et al., 1999). The lower pressure levels allow SCGs to be worn for longer periods of time without discomfort or detrimental effects (MacRae et al., 2011).

2.3 Ergogenic Aids in Sport

Since the foundation of the Modern Olympic Games in 1896 athletic performance has continually grown. Running performance has grown by 10-30% (Haake et al., 2014), evident in 36 new men’s marathon world records since 1908 (Foster et al., 2010), despite only small variations in weight and height measurements (Rosenbaum, 1988). A combination of globalisation, population growth, technological developments as well as drugs and training interventions are thought to have caused this growth in sports performance (Haake et al., 2015). However, in more recent years performance discrepancies among elite athletes in many competitive sports have become smaller with some disciplines reaching saturation point (Senner et al., 2009). As a result, often a tenth of a second can make the difference between winning a gold or a silver medal, leading to heightened competition in elite sports. Athletes in search for ‘the edge’ increasingly utilise ergogenic aids in the hope of improving their performance, even if effects are only marginal.

Ergogenic aids in the context of sports are techniques and substances applied to directly or indirectly improve physiological variables, resulting in enhanced energy production and performance (Thein et al., 1995; Robergs, 2010). They encompass an extensive list of interventions applied during exercise or recovery, ranging from steroids to hypnosis and can be divided into five main categories: nutritional, pharmacological, mechanical, psychological and physiological (Thein et al., 1995; Robergs, 2010). It is, for example, common practice to use performance diagnostic, nutrition plans and intensive sport scientific mentoring through experts, whilst employing precision-engineered sports equipment and body positions. In addition to these central factors, clothing plays an important role in the attempt to gain an advantage over the competition (Chowdhury et al., 2009; Senner et al., 2009; Moria et al., 2010).

Haake (2009) developed a performance improvement index that allows comparisons of athletic performance over time between athletes and sports. His performance improvement index for 100-metre sprints indicated that 4% of the 24% performance increase between 1896 and 2008 could be associated with tighter, more aerodynamic clothing. The use of clothing to enhance performance first grabbed mainstream attention in 2000 during the Olympic Games in Sydney, where Speedo's Fastskin swimsuits, mimicking shark skin to reduce drag, were introduced, leading to a performance increase of about 0.9 to 1.4% in men's freestyle (Foster et al., 2012). Eight years later, in the Beijing Olympic Games performance was further improved with an incomparable number of world records being set. This was associated with the introduction of polyurethane panels ('Speedo LZR') and later the introduction of all-over polyurethane suits ('Arena X-Glide') and led to FINA (Fédération Internationale de Natation), the governing body of swimming, banning full length body suits using 'non-fabric' materials in 2010 (Foster et al., 2012). This sparked the question of whether sports engineering is fair or should be classed as technological doping. It is a controversial topic with an abundance of strong opinions. On the one hand there is the idea that advances in sports engineering have made many sports disciplines safer and more accessible, while on the other hand there are concerns that it has led to passiveness of athletes and unfair advantage (James, 2010).

SCGs are a form of ergogenic aid as they are claimed to improve exercise performance and shorten post-exercise recovery time. They are regarded as a safe intervention to legally manipulate human physiology (Perrey, 2008).

In order to understand how SCGs work it is crucial to have a sound understanding of the human body and its behaviour during exercise and recovery. This background information is provided in Appendix A.

2.4 Sports Psychology

There are many aspects of sports psychology, but according to Vealey (2001) the influence of self-confidence on sports performance is particularly interesting. While there has been a lot of research suggesting that self-confidence is related to sport success (e.g. Vealey, 1986; Feltz, 1988; Feltz, 1994), a full understanding of this area is still lacking.

In a four-phase study using over 500 athletes Vealey and colleagues (1998) identified relevant sources of confidence for athletes. The researchers defined nine sources of sport confidence within three main domains: achievement, self-regulation and social climate. The findings of the study suggest that athletes gain confidence through physical/mental preparation, social support, mastery, demonstration of ability, and physical self-presentation. According to the study, physical self-presentation and social support are more important factors in increasing self-confidence for females than males. The importance of physical self-presentation for female athletes indicates the significance of body image satisfaction to female self-confidence and sports performance.

Body image is the way individuals perceive their own outer appearance (Thompson et al., 1999). Body image dissatisfaction is the result of a comparison of one’s current and ideal body shape (Feltz, 1988). Physical activity can alter body shapes depending on whether the activity is anaerobic, promoting muscle bulk, or aerobic, promoting lean body shapes. The resultant body shapes may not represent the female body ideal, which can lead to body image dissatisfaction in athletes and in turn can affect self-confidence (Swami et al., 2009; Kopczynski and Vogelsang, 2011). However, there is no consensus about whether or not female athletes have a lower level of body image satisfaction than the general population (Swami et al., 2009). Opinions also diverge on whether self-confidence is lower in female athletes or male athletes. However, there seems to be a consensus that a strong level of self-confidence has a positive effect on sports performance. As a result, coaches and mentors try to enhance athletes’ confidence. However, as Vealey (2001) points out, no mental training can instil self-confidence unless the physical requirements are being met. So while self-confidence plays a crucial part in sports performance, performance itself can also increase self-confidence. In a recent Mintel (2014) survey of sporting goods consumers 14% of respondents stated that they buy new sporting goods to be more confident in their ability when participating in sport. This shows that some sportswear users are actively seeking ways to improve their confidence.

A small-scale qualitative survey conducted by Beedie (2007) suggested that 73% of respondents have experienced a placebo effect in sport. A placebo effect is “a favourable outcome arising purely from the belief that one has received a beneficial treatment” (Clark et al., 2000:1642). It is well-established practice in medical research, where it is used to test new drugs in placebo-controlled conditions. The beneficial effects of ergogenic aids, such as SCGs, could be elicited by a placebo effect giving the wearer a psychological edge. The difficulty lies in measuring a placebo effect in SCGs, as it is impossible to blind participants due to differences in tightness of SCGs and placebo garments. However, attempting to lessen an individual’s faith in the mechanical factors of SCGs could reduce the influence of a placebo effect on performance (Beedie, 2007).

SGCs could provide athletes with the boost needed to break their personal best. The underlying reasons could be manifold and are likely to be different to each individual. SCGs could for instance provide a psychological lift to wearers suffering under body image dissatisfaction or increase the wearers’ confidence in their ability because they believe in the physiological effects of SCGs on their body. There is currently a lack of research investigating the psychological effects of SCGs on athletes.

2.5 Pressures Applied by Sports Compression Garments

2.5.1 Pressure Levels

The purpose of SCGs is to apply pressure to the underlying body. There is currently no consensus on the optimum level of pressure that SCGs should elicit to improve sports performance and post-exercise recovery. Lawrence and Kakkar (1980) established the level of pressure in graduated compression stockings that would lead to the fastest venous return: 18mmHg at the ankle, 14mmHg at the calf, 8mmHg at the knee, 10mmHg at the lower thigh and 8mmHg at the upper thigh. However, their research was based on compression for medical purposes and more research is needed to determine pressure levels for optimum haemodynamics in healthy athletes (Brophy-Williams et al., 2015). As discussed in section 1.1.1, the effects of compression in sports are not restricted to increasing blood flow, other claimed benefit are the reduction of muscle oscillation and improvement of proprioception. These diverse compression effects may require different pressure levels and profiles for optimal results (MacRae et al., 2011; Born et al., 2013). The same is true for medical compression, where the recommended pressure range for the treatment of burn scars is 15 to 24mmHg (Macintyre and Baird, 2006; Macintyre, 2007; Aiman et al., 2016), whilst pressure levels for haemodynamic effects can be much higher depending on the compression class (refer section 2.2). Pressure levels defined by SCG brands seem to be more arbitrary than based on empirical evidence (MacRae et al., 2011). Further research is needed to identify optimal pressure levels for different compression-related effects and wear environments (e.g. exercise type, location on body) (MacRae et al., 2016).

Compression levels of SCGs from different brands vary widely. Researchers also reported that pressures within one size category of compression tights varied widely across individuals due to variations in body shapes and limb girths of individuals of the same height and weight (Hill, Howatson, van Someren, Walshe, and Pedlar, 2014; Brophy-Williams et al., 2015). Not much is known about the pressure levels exerted by different sized garments of the same brand (Brophy-Williams et al., 2015). Perrey (2008) suggested that the pressure quoted by a brand is likely to be valid for one individual person only.

A number of researchers (e.g. Ali et al., 2007; Ali et al., 2010; Dascombe et al., 2011; Miyamoto et al., 2011; Sperlich, Haegele, et al., 2011; MacRae et al., 2012; Miyamoto and Kawakami, 2014; Zinner et al., 2017) used different pressure levels in the same exercise protocol (e.g. over- and/or under-sized SCGs), however their findings on the effects on sports performance and recovery were mixed and do not allow for a conclusion on minimal or optimal pressure levels required. More recently, researchers (e.g. Hill et al., 2017; Smale et al., 2018) have compared the effects of SCGs and MCS on post-exercise recovery and performance. Hill and colleagues (2017) found significant improvement in maximal voluntary contraction and counter movement height when wearing MCS during post-exercise recovery, but not when wearing sports compression tights. Whilst Smale et al. (2018) reported no effects on performance for either MCS or sports compression tights, however they highlighted a potential improvement in cognitive accuracy during high-intensity cycling.

According to the SCG specialist 2XU (2015), the pressure range applied by their SCGs is 20 to 30mmHg with a 25% gradual reduction in pressure from the ankle to the top of compression tights. The brand states that they would not apply more than 40mmHg, as it can have adverse effects; a view shared by Ng (1995).

It is not fully understood how pressure levels transfer to the underlying tissues of the body. The experimental study by Giele and colleagues (1997) measured subdermal pressure without compression and with compression applied to the calf on one leg (medial calf 36mmHg, posterior calf 66mmHg, medial lower calf 59mmHg) using a measurement needle, whilst Uhl and colleagues (2015) measured intramuscular pressure at the medial calf at different pressure levels (0mmHg to 50mmHg) in supine and standing positions. The findings from Giele et al. (1997) led the researchers to the conclusion that interface pressure measured over soft tissue generally overestimates pressure, whilst interface pressure measured over bony prominences underestimates pressure compared to subdermal pressure. Intramuscular pressures measured in the study by Uhl et al. (2015) were higher than interface pressures, but there was a linear correlation between the two pressures in standing position and for pressure values above 20mmHg in supine position. These findings are only based on very small samples. Further research is needed to fully understand the effects of interface pressure on underlying tissue, which could advance the determination of optimal pressure levels for different purposes.

Different body postures and movement can alter pressure levels applied to the wearer’s body. Researchers have started to examine the effects that posture and size could have on pressure levels. Brophy-Williams et al. (2015) found that a standing posture and smaller sizes elicited the highest level of pressure, whilst oversized garments worn in a seated position presented the lowest compression. The pressure profiles differed and were neither degressive nor progressive. Hill, Howatson, van Someren, Walshe, and Pedlar (2014) reported that applied pressures of compression tights were higher during muscle contraction compared to the anatomical position. Riebe et al. (2015) identified variations of 5-10mmHg when comparing anatomic and tiptoe postures of MCS, whilst Blättler et al. (2007) found variation of up to 15mmHg under similar conditions.

Pressure changes occur due to variations in body circumferences, skin deformation and curvature of the body (Partsch, Clark, et al., 2006; Luo et al., 2016), however, the degree of change varies widely across individuals (Partsch, Clark, et al., 2006). It is, therefore, difficult to make general predictions on how pressures applied by SCGs change during wear. Fabric behaviour is also difficult to predict due to the non-linearity of stretch and deformation properties of fabrics (Troynikov et al., 2010).

Generally, pressure increases when a joint, such as the knee, is flexed during dynamic movement (Perrey, 2008; Troynikov et al., 2010), potentially resulting in large pressure fluctuations during dynamic movements that require joint flexion, such as running. This could have implications on comfort, as the garment might feel too tight after prolonged wear. A direct relationship between tightness of compression exerted and comfort exists (Perrey, 2008).

2.5.2 Measuring Pressure Levels

A variety of different sensors are available to quantify the level of pressure applied by CGs. Most studies examining pressure measurement (PM) devices originated from the medical field. There is currently no widely agreed and validated test method to measure pressure levels applied by CGs (Perrey, 2008; Thomas, 2014b). It is common to measure pressures applied by MCS in vitro on wooden leg surrogates or cylinders, whilst studies on the effects of SCGs that quantify pressure tend to measure pressure in vivo. It has been shown by Sawada (1993) that PMs are affected by differences in the underlying surface texture. The researcher simulated fatty tissue and body prominences by using sponges and plastic plates and found significant differences in pressure delivery. However, how these variations translate to in vivo measurements is unclear. Ng (1995) reported that pressure values were 5% and 10% lower when measured on lower and upper human limbs, respectively, compared to cylindrical tubes.

Researchers from both the medical (Partsch, Partsch, et al., 2006) and sports science (Brophy-Williams et al., 2014) fields have since recommended the measurement of pressure in vivo as variations in body composition and posture can be taken into account increasing the ecological validity of the measurements.

Advantages of measuring pressure in vitro are that measurements using the same test method are comparable (MacRae et al., 2016). In vitro measurements can also be advantageous when analysing the effects of fabric or garment characteristics on pressure (e.g. Kumar et al., 2013). However, since SCGs are worn on a moving body, in vivo measurements should be the preferred method when assessing pressure levels. Although, it needs to be considered that body tissue, movement and posture as well as the exact location of a measurement influence in vivo pressures (MacRae et al., 2011), reducing reproducibility of studies.

Accuracy of PMs varies depending on the method used. This can cause confusion as some brands claim that their SCGs elicit a certain amount of pressure without stating how compression was measured. As Perrey (2008:325) puts it: “Compression data means nothing if the method used cannot be proven to be reliable and valid.”.

2.5.2.1 Pressure Measurement Methods

The pressure applied by SCGs is typically measured by placing sensors at the interface of the SCG and the wearer’s skin. PMs can vary significantly depending on the measurement location on the body and the location along the circumference (Liu et al., 2005; R. Liu et al., 2007b; Sperlich, Born, Kaskinoro, et al., 2013; Miyamoto and Kawakami, 2014). It is, therefore, critical to use standard measurement locations (Ng, 1995). Researchers from the medical field have provided guidelines for PMs on lower limbs (Comité Européen de Normalisation, 2001; Partsch, Clark, et al., 2006). Pressure levels at the ankle are generally used as reference for MCS manufacturers to indicate pressure values. However, circumferences at the ankle can vary widely across individuals due to bony prominences and tendons in this area, which could result in varying pressure levels across individuals (Partsch, Partsch, et al., 2006). Whilst there are currently no standardised measurement locations for SCGs, MacRae et al. (2011) recommended the following three PM locations as standard sites for the assessment of lower body SCGs in order to improve consistency across studies:

- B1: area where Achilles tendon changes into calf muscles,
- C: calf at maximum girth,

- F: mid-thigh.

Additional measurement locations used should be clearly described as well as the participants' posture (Partsch, Clark, et al., 2006). There are no clear guidelines on PM locations for the upper body as not many studies have measured upper body compression.

In order to better understand the measuring conditions, Partsch et al. (2006) recommended reporting the following information:

- Location of the sensors,
- Movements carried out by participant,
- Circumference of the leg segment where the sensors are placed,
- Smallest circumference of the leg,
- Room temperature,
- Exact time of when measurements are taken after compression has been applied,
- Time of the day.

Even when standardised PM methods are used, it is difficult to evaluate pressures, i.e. understand why one SCG applies a higher level of pressure than another. This is due to the complex effects of garment, fabric and body characteristics on pressure, which are often not clearly or precisely measurable (Hohenstein Institute, 2018b).

2.5.2.2 Pressure Measurement Technologies

A number of different PM devices based on different sensor technologies have been utilised to measure pressures applied by SCGs. They can be classified into three categories: Pneumatic, fluid-filled and resistive. The advantages and limitations of the three types of sensors have been summarised in Table 2.2.

Table 2.2: Advantages and limitations of three types of pressure sensors (adapted from Partsch, Clark, et al., 2006:227)

Sensor type	Advantages	Limitations
Pneumatic	Thin and flexible sensors; inexpensive	Sensitive to temperature and hysteresis
Resistive	Thin sensor; dynamic measurement possible	Sensitive to curvature; stiff and thick; not useful for long-term measurements
Fluid-filled	Flexible; dynamic measurement possible	Thick when filled; problem during motion

Partsch et al. (2006) compiled a list of important requirements for pressure sensors (see Figure 2.2). The key requirement for pressure sensors are that they are flexible and thin, so that they can adapt to the shape of the anatomical site and do not modify the mechanical properties of the garment-skin-interface (Ng, 1995). Technical accuracy of sensors is crucial, however, when intended for the application of in vivo PMs, practical issues, such as portability, fast and simple set up and measurement and recording of data, need to be considered (Flaud et al., 2010; Tyler, 2015). The most widely used commercial PM systems in the context of CGs are presented in Table 2.3. The Kikuhime (Meditrade, Sorø, Denmark) and PicoPress® (Microlab, Padova, Italy) pneumatic PM devices, which have been proven to provide valid and reliable PMs (Van den Kerckhove et al., 2007; Mosti and Rossari, 2008; Partsch and Mosti, 2010; Brophy-Williams et al., 2014), were the most popular PM devices for CGs alongside the SIGaT Tester (Ganzoni-Sigvaris, St Gallen, Switzerland). Additionally, the FlexiForce® and I-Scan® systems (both: Tekscan, South Boston, MA, USA) have been applied in the research context of CGs. Some researchers have developed custom PM devices (e.g. Maklewska et al., 2007; Baldoli et al., 2016; Oner et al., 2017; Zhou et al., 2017), however, these are currently at experimental stage and not commercially available.

Several researchers have evaluated and/or compared different sensors (e.g. Flaud et al., 2010; McLaren et al., 2010; Partsch and Mosti, 2010; Brophy-Williams et al., 2014). Whilst many of the available sensors meet some of the criteria listed in Figure 2.2, none of them fulfils all of the requirements. Hence, selecting a sensor always results in compromises (Partsch, Clark, et al., 2006; Baldoli et al., 2016).

Sensor Design

- Thin
- Variable sensor sizes
- Size – insensitive to force concentrations
- Flexibility – insensitive to bending, but not distensible
- Insensitive to temperature and humidity changes
- Simultaneous use of multiple sensors
- Durability
- Overload tolerance
- Low cost

Measurement Competence

- Accuracy
- Reliability
- Low hysteresis
- Operating range consistent with biological parameters
- Linear response to applied pressure
- Continuous output - during active or passive movement
- Easy calibration

Figure 2.2: Summary of desirable requirements for pressure measurement devices (Partsch, Clark, et al., 2006)

Table 2.3: Most prominent commercial pressure sensors to measure pressures applied by CGs

Sensor type	Pressure measurement system	Studies using PM device
Pneumatic	Kikuhime (Meditrade, Sorø, Denmark)	***Medical:*** Partsch (2005); Mosti and Mattaliano (2007); Fukushima et al. (2017) ***Sport:*** Scanlan et al. (2008); Sear et al. (2010); Trenell et al. (2006); Sear et al. (2010); Brophy-Williams et al. (2015); Hill et al. (2015)
	PicoPress® (Microlab, Padova, Italy)	***Medical:*** Mosti and Partsch (2010, 2011, 2012); Lattimer et al. (2013); Rimaud et al. (2014); Chassagne et al. (2015); Riebe et al. (2015) ***Sport:*** Faulkner et al. (2013); Kerhervé et al. (2017a); Leoz-Albaurrea (2016); Piras and Gatta (2017); Reed et al. (2017)
	Oxford Pressure Monitor (Talley Ltd, Romsey, UK)	***Medical:*** Mayrovitz and Larsen (1997); Wildin et al. (1998); Best et al. (2000); ***Sport:*** no known studies
	Talley SD500 Skin Pressure Evaluator (Talley Ltd)	***Medical:*** Williams et al. (1998) ***Sport:*** Pruscino et al. (2013)
	MST MKIII Salzmann (Salzmann Medico, St Gallen, Switzerland)	***Medical:*** Liu et al. (2013) ***Sport:*** Maton et al. (2006); Struhar et al. (2018)
	SIGaT Tester (Ganzoni-Sigvaris, St Gallen, Switzerland)	***Medical:*** Blättler et al. (2007) ***Sport:*** Born et al. (2014); Sperlich et al. (2011; 2013; 2013); Wahl et al. (2012); Zinner et al. (2017)
Resistive	I-Scan® (Tekscan, South Boston, MA, USA)	***Medical:*** MacIntyre et al. (2004); MacIntyre (2007) ***Sport:*** Venckunas et al. (2014)

Sensor type	Pressure measurement system	Studies using PM device
	FlexiForce® (Tekscan)	***Medical:*** Liu et al. (2005; 2007b) ***Sport:*** Yan et al. (2014)
Fluid-filled	Strathclyde Pressure Monitor (University of Strathclyde, Glasgow, Scotland)	***Medical:*** Barbenel et al. (1990); Sockalingham et al. (1990); Nelson (2001) ***Sport:*** No studies

Kikuhime

The Kikuhime system was originally developed to determine the pressure under bandages in the medical field. The PM device consists of an oval, air-filled polyurethane pressure bladder of 30 x 38mm dimension that is filled with a 3mm thick foam (Brophy-Williams et al., 2014; Advancis Medical, 2015; Tyler, 2015). The sensor connects to a measuring unit with pressure transducer via a silicone tube (Brophy-Williams et al., 2014; Tyler, 2015). The device is capable of handling multiple sensors in order to measure pressure at various locations. Pressure values are continually displayed on the PM device in real time in 1mmHg increments.

Brophy-Williams and colleagues (2014) assessed the validity and reliability of the Kikuhime PM device, which is widely used to determine pressure applied by SCGs in research (e.g. Trenell et al., 2006; Ali et al., 2010; Sear et al., 2010; Lovell et al., 2011; De Glanville and Hamlin, 2012; Hamlin et al., 2012; Hill, Howatson, van Someren, Walshe and Pedlar, 2014). In order to validate the Kikuhime measuring device, Brophy-Williams and colleagues (2014) used three individual Kikuhime sensors and measured pressures inside a water column at 5mmHg increments ranging from 5 to 100mmHg, which demonstrated it to be a valid instrument. The researchers further tested the reliability of the Kikuhime device in an in vivo test situation with five testers measuring pressure under sports compression tights (2XU) on an athlete’s body in standing position. Results showed that the Kikuhime device is a valid and reliable instrument to directly measure the pressure applied by SCGs to the underlying body.

PicoPress®

The PicoPress® system is a portable digital PM device. Like the Kikuhime system, it was developed for medical purposes (Rimaud et al., 2014; Microlab Elettronica, 2015). The very thin (200µm) and flexible sensor consists of a circular bladder with a 5cm diameter made from a biocompatible material (Microlab Elettronica, 2015; Tyler, 2015). The sensor is connected to the handheld digital microprocessor gauge via a tube. 2cm^3 of air are inserted manually into the bladder by activating the micro pump on the handheld device (Rimaud et al., 2014; Microlab Elettronica, 2015). The pressure is measured by a manometer as the expansion of the bladder is constrained by the garment or bandage (Tyler, 2015). The pressure value is shown in real time via a digital display in mmHg. Unlike the Kikuhime system, it can be calibrated when under the bandage; hence it can be left under a bandage for a prolonged period of time. The PM device connects to a software that enables the measurement of dynamic pressure (e.g. lying, standing, walking, resting) (Mosti and Rossari, 2008; Tyler, 2015). The PicoPress® system is regarded as reliable and reproducible as demonstrated by existing research (Mosti and Rossari, 2008; Partsch and Mosti, 2010).

Tekscan

Tekscan offers very thin resistive sensors in a variety of sizes and alongside a data-processing and -visualisation software (Tyler, 2015). Researchers (Ferguson-Pell et al., 2000; Macintyre, 2011) have reported problems with drift, however the sensors have been shown to provide accurate results with the right calibration approach (refer Macintyre, 2011) and standardised measurement protocol (Tyler, 2015).

FlexiForce® system:

FlexiForce® sensors can be used to measure contact force (Ferguson-Pell et al., 2000), however, they cannot map pressure distribution (Tyler, 2015). Ferguson-Pell et al. (2000) evaluated the FlexiForce® sensor and concluded that the drift, repeatability, linearity and hysteresis of the sensor were acceptable and that the sensor is suitable for usage on flat surfaces or curved surfaces with radii greater than 32mm under static conditions. More recently Parmar and colleagues (2017) found FlexiForce® sensors to be accurate for static PMs, but not for dynamic ones, calling into question the sensor’s usefulness for in vivo PMs. This sensor was used by Allsop (2012) for in vitro PMs of compression tops.

I-Scan® system:

I-Scan® sensors measure applied pressure through linear changes to the pressure-sensitive interlayer of the sensor, which is located between two sheets of thin polyester coated with electrical conductors (Tyler, 2015). Macintyre (2011) developed a suitable method to calibrate I-Scan® sensors to ensure precision of measurements.

Potential problems with using sensors

Thomas (2014a) examined the accuracy of the Kikuhime and PicoPress® hand held pneumatic instruments to measure pressures produced by extensible bandages. He found that the pneumatic pressure sensors were a lot less accurate than is commonly believed. He called into question the validity of many published studies that rely upon these PM devices. The two reasons the researcher stated for this claim were the position of the sensor on the limb due to variations in body surface texture and the mode of action and method of calibration.

Although the presented PM devices feature very thin sensors, they can locally modify the curvature of a limb when placed between the garment and the skin. This is especially true for pneumatic PM devices. The curvature modification can then lead to distortion of the pressure applied at the location (Al Khaburi et al., 2011; Tyler, 2015; Chassagne et al., 2016). Chassagne and colleagues (2016) developed a model to eliminate this measurement error. The researchers found that errors are particularly prevalent in lower pressure ranges. The reduction of errors with higher pressure values can be explained through the increased penetration of the sensor into the soft tissue with increased pressure application, which reduces curvature modification. However, the use of correction models is difficult and not suitable for clinical application (Al Khaburi et al., 2011). New developments in PM devices should design even thinner sensors to avoid affecting local curvature over the measured area.

Developments in dynamic pressure measurement methods

SCGs are designed to be worn during exercise when the body is in motion. Body movement affects pressure levels due to changes in body dimensions and fabric tension. Hence, neither in vitro nor static in vivo PMs can provide a full assessment of the pressures applied to the body during exercise. The discussed PM systems are all connected to a device, not allowing unrestricted movement, thus in vivo measurements are generally taken with participants in a standing, immobile posture. It would be most useful to measure compression while the body is in motion. A device that can measure pressure during dynamic movement of the body has been developed by Skins (SKINS International Trading AG, Steinhausen, Switzerland) (McLaren et al., 2010) in collaboration with a scientific and industrial research organisation in Australia, but unfortunately the measuring device and knowledge is the property of Skins and not available on the free market. Whilst dynamic PM devices for in vivo measurement are currently not commercially available, pressure can be measured in different body postures in addition to the anatomical position (MacRae et al., 2011), which can give indications into the way pressure behaves during movement.

Recent research on the development of a smart CG with integrated pressure sensors (Belbasis and Fuss, 2015; Belbasis et al., 2015a, 2015b) could facilitate the analysis of compression during exercise. The smart CG could provide more detailed insights into the effects of body movement and related muscle contractions on applied pressure levels.

A test method for measuring both static and dynamic pressure of medical compression textiles in vitro according to DIN 58133 was developed by Hohenstein in the 1980s (HOSY) and has recently been updated with a new hardware and software package (HOSYcan) for improved evaluation options (Hohenstein Institute, 2018a). In the testing process, the test fabric is stretched to a pre-determined extension identified by the garment size. Force is measured at 20 locations, 5cm apart, along the length of the test fabric (see Figure 2.3). Using mathematical formulas, including Laplace’s Law, the pressure applied to the body in relation to the circumference is calculated. The HOSY system can simulate movement sequences and determine pressure levels at different parts of the body. Body measurements obtained through three-dimensional body scanning can be input into the system to customise movement profiles (Hohenstein Institute, 2018b). The system sounds promising, but independent evaluations of the system assessing its reliability and in vitro-in vivo measurement correlations are yet to be produced.

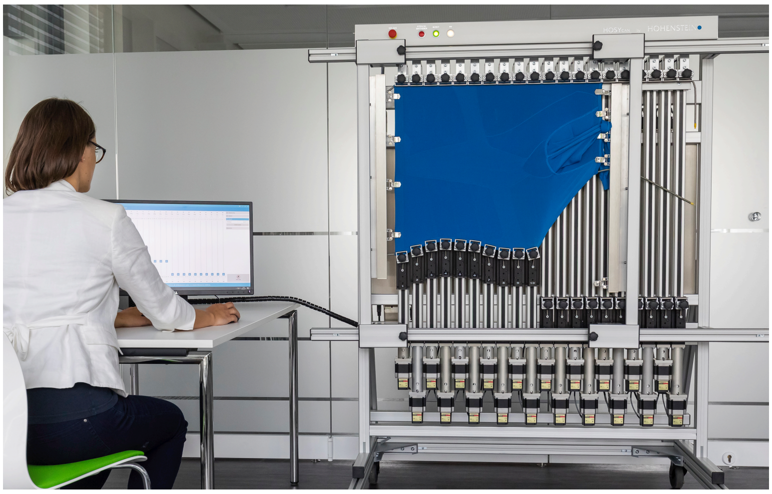


Figure 2.3: HOSYcan system for measuring static and dynamic compression (Hohenstein Institute, 2018b)

2.5.3 Laplace's Law

Laplace's Law in its original form was developed to relate the pressure gradient across closed elastic membranes or liquid film spheres, such as droplets or soap bubbles, to the tensions in the membrane or film (refer Eq. 2) (Macintyre, 2007; Thomas, 2014b).

$$P = \frac{T}{R} \qquad \text{(Eq. 2)}$$

where P = pressure in Pascal, T = tension in the wall in Newtons per metre and R = radius of curvature in metres.

Laplace's Law has been widely used to calculate pressures in physical chemistry, chemical engineering and the medical sciences (Thomas, 2014b). In the medical sciences it has been used in the context of cylinders (e.g. blood vessels) (Macintyre, 2007). In recent years, the equation has been applied to assess the level of pressure elicited by a fabric under known tension to a limb of known radius (R. Liu et al., 2017). In the context of CGs, Laplace's Law dictates that the pressure applied by CGs with constant fabric tension results in lower pressure application for bigger limbs. A modified version of the law was introduced by Thomas (2003), which had the purpose of making Laplace's Law suitable for the prediction of pressures applied by medical compression bandages. The modified version (refer Eq. 3) included bandage width and the number of layers applied and used limb circumference rather than radius to facilitate usability in clinical practice. Thomas also converted the units to more commonly use units in the medical field.

$$P = \frac{T \times n \times 4620}{C \times W} \quad \text{(Eq. 3)}$$

where P = pressure in mmHg, T = bandage tension in Kgf, n = number of layers applied, C = circumference of the limb in cm and W = width of the bandage in cm (the constant 4620 is derived from the conversion of units).

Macintyre (2007) modified Laplace's Law for the use of tubular MCGs (refer Eq. 4). Like Thomas (2003), the researcher modified the equation so that limb circumferences rather than radii could be used and so that resultant pressure values were in mmHg.

$$P = (4.713T)C^{-1} \quad \text{(Eq. 4)}$$

where P = pressure in mmHg, T = fabric tension in N m^{-1}, C = circumference of the limb in cm (the constant 4.713 is derived from the conversion of units).

Macintyre (2004; 2007) applied compression sleeves of known tension to cylinders and human thighs and forearms of varying circumferences and compared pressures calculated by the modified Laplace Law (Eq. 4) to pressure measurements using I-Scan® sensors (Tekscan, USA). The researcher concluded that pressures could only be accurately predicted using Laplace's Law for circumferences larger than 30cm under known fabric extension and tension.

The biggest criticisms of applying Laplace's Law to calculate the expected level of pressure that a CG will apply to a wearer's body lie in the facts that the law does not take into account variations in tissue structure (e.g. fatty or muscular tissue, bony prominences) and curvature (Basford, 2002). Figure 2.4 shows the cross-sectional contours of a limb at different levels as observed on magnetic resonance images (MRIs). The apparent irregularities of radii along the cross-sections translate into variations in pressure levels applied by a MCS (Liu et al., 2005; R. Liu et al., 2017). These variations in pressure can be measured by point measurements using PM devices, however the modified Law of Laplace is unable to provide this detail, as it provides the average pressure exerted across a limb's circumference (Thomas, 2014b). So it is important to consider that point pressure values can vary significantly from the average pressure calculated with the modified Law of Laplace.

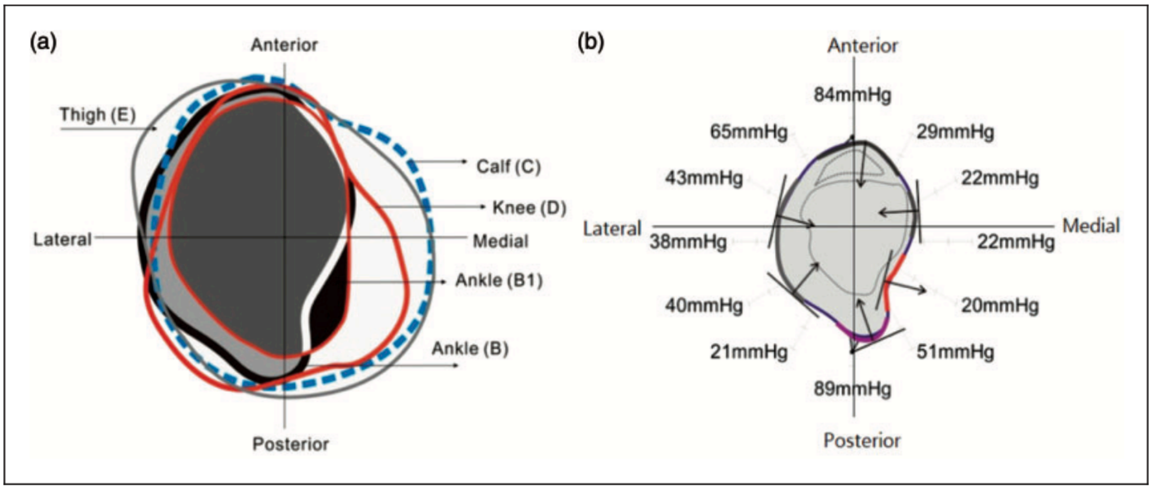


Figure 2.4: Effect of radius of curvature of pressure application: a) cross-sectional contours of a human leg at different levels of the limb; b) pressure values measured at different points along the cross-section of the ankle (B) (R. Liu et al., 2017)

It has been highlighted that the use of the original Law of Laplace would be more suitable, as it uses radius rather than circumference measurements (Schuren and Mohr, 2008). Schuren and Moor (2008) compared the PMs taken from 744 compression bandages applied to artificial legs equipped with pressure transducers with theoretical compression forces calculated by Thomas's (2003) modified Laplace equation (Eq. 3). The results showed that the calculation using this equation did not provide reliable prediction of the actual measured sub-bandage pressures. However, it needs to be considered that sub-bandage pressure can be influenced by the technique and experience level of the bandagers (experts were used in their study). Thomas (2014b) argued that Schuren and Moor's (2008) conclusion was inappropriate, as it is generally not appropriate to correlate predicted pressure values with point measurements on limbs when assessing the modified Laplace Law as the positioning of the sensor would affect pressure levels (Thomas, 2014b). He suggested using average values instead and questioned studies reporting a lack of graduated compression based on point measurements across the limb.

It needs to be considered that Laplace's Law is a simplified calculation that does not take into account body surface texture (Maklewska et al., 2006) or variations in fabric tension during wear (R. Liu et al., 2007b; Schuren and Mohr, 2008). It does further not consider fabric friction or longitudinal fabric stretch (Troynikov et al., 2010). All these aspects can influence applied pressure levels. The original Law of Laplace (Eq. 2) is difficult to apply in practice, as it is complicated to obtain radii of curvature of the human body. The modified versions of Laplace's Law (Eq. 3 and 4) using circumference measurements cannot predict pressures of SCGs across the whole body. The equations are not accurate for non-circular shapes, such as the human torso, or small circumferences, such as lower arms and lower legs and as such should be applied with caution in the prediction of pressures applied by SCGs. However, the modified Laplace Law can provide an average pressure indication for limbs of a circumference larger than 30cm (Macintyre, 2007).

2.6 Evidence for the Effects of Sports Compression Garments

2.6.1 Measuring Effects of Sports Compression Garments

Most studies measuring the effects of SCGs on exercise performance or recovery use randomised, crossover study designs. A selected number of parameters are measured before, during and/or after exercise for a control condition and for the SCG treatment condition. Variations in the measured parameters are then compared to identify the effects of wearing SCGs. However, some studies also apply pair-matched study designs (e.g. Carling et al., 1995; Fedorko, 2007; Welman, 2011; Hill, Howatson, van Someren, Walshe and Pedlar, 2014; Areces et al., 2015; Zaleski et al., 2015; Hill et al., 2017; Kim et al., 2017; Upton et al., 2017). With large inter-individual variations in responses to SCG treatment reported in existing research (e.g. Laymon, 2009; Stickford et al., 2015) repeated measures cross-over designs should be the preferred way of measuring effects of SCGs.

2.6.1.1 Mechanical and Physiological Parameters

Sports scientists use a large number of different parameters to assess sports performance or recovery. There is a distinction between mechanical and physiological parameters (Phillips, 2015). A list of different parameters and measuring intention is given in Table 2.4.

Table 2.4: Examples of mechanical and physiological parameters measured to assess sports performance and recovery

	Mechanical parameters	Physiological parameters
Performance	• Exercise time • Distance covered • Total workload • Maximum voluntary force generation • Time to exhaustion	• Blood pH • Oxygenation • VO_2 (max) • Heart rate • Haemoglobin

	Mechanical parameters	Physiological parameters
Recovery	• Subsequent workout performance parameters (see above)	• Lactate • Creatine kinase • C-reactive protein

In recent years, researchers (e.g. Hsu et al., 2017; Kurz and Anders, 2018) have also started to employ surface electromyography (EMG) to assess the effects of compression on muscle activation.

2.6.1.2 Perception

Another important aspect, given less attention in SCG research, are measures of perception. A large variety of different rating scales exist within the sports science field to assess factors such as perceived exertion or pleasure during exercise or perceived muscle soreness post-exercise (i.e. delayed onset muscle soreness (DOMS)). The most commonly used scale is the Borg scale for ratings of perceived exertion, which provides a holistic measure of exertion (Phillips, 2015).

What researchers assessing the functionality of SCGs have neglected is the way SCGs make wearers feel, i.e. psychological comfort. The social role of an athlete is associated with certain norms and behaviours. It may or may not be in line with the self-identify of the athlete (Kleine et al., 1993; Dickson and Pollack, 2000). Clothing can support merging the social role and self-identity by symbolising the athlete's role. This could, on the one hand, facilitate the individual's acceptance in the role by others and, on the other hand, convince the self-identity that the wearer has certain qualities that are important to the role (Belk, 1988). As such, clothing can aid athletes in creating an identity with their sports role (Dickson and Pollack, 2000). In the context of this study, wearing SCGs could install wearers with the feeling that they have the ability of a fast runner and, hence, experience a psychological lift by wearing SCGs due to increased self-esteem.

Kraemer and colleagues (1998) assessed their participants' perception of how they felt the SCGs used in the investigation had contributed to their repeated jumping performance without providing performance feedback. The male participants indicated a significant perception of improvement in vertical jump performance when wearing compression shorts compared to the control condition of no compression. Ali and colleagues (2007, 2010) also included a 'comfort and feel rating' (comfort, tightness and pain) associated with wearing compression socks during exercise in their study analysing the effects of compression socks on intermittent and continuous running exercises. More recently, Brophy-Williams and colleagues (2017) asked participants about their beliefs in the efficacy of SCGs. A sensation of comfort during exercise and a positive attitude towards SCGs can contribute to performance-enhancing properties of SCGs (Hooper et al., 2015; Brophy-Williams et al., 2017). However, more research is needed to confirm this, as existing research has not analysed the relationship between perceived comfort and performance.

2.6.1.3 Mechanisms of Sports Compression Garments

Exact mechanisms of SCGs are yet to be explained, but it is likely that they differ during different exercise types (e.g. strength, endurance) and during recovery, owing to the different physical conditions. Born and colleagues (2013) identified five different categories of effects of SCGs on the human body: haemodynamic, mechanical, neuromuscular, thermal and psychological effects. They summarised the main hypotheses related to the underlying mechanisms producing these effects as listed in Table 2.5. It has been speculated that haemodynamic effects are most likely responsible for the recovery-enhancing effects of SCGs through faster clearance of metabolic waste products and increased oxygen delivery (Bringard et al., 2006; Beliard et al., 2015). Mechanisms supporting the body during exercise are likely to be associated with mechanical effects, such as decreasing muscle vibration, which can reduce muscle microtraumatism (Beliard et al., 2015). Couturier and Duffield (2013) suggested that mechanical and neuromuscular effects could potentially be of more interest than 'traditional' haemodynamic effects of SCGs.

Table 2.5: Potential mechanisms underlying the effects of SCGs (adapted from Born et al., 2013:14)

Effect	Hypothesis	References
Haemodynamic 1	Decrease in diameter of superficial veins ➔ Decrease in superficial blood flow ➔ Increase in deep vein blood flow ➔ Increase in muscle pump and valvular function during exercise ➔ Increase in venous blood return to the heart ➔ Increase in stroke volume	Lewis et al. (1976); Lawrence and Kakkar (1980); Ibegbuna et al. (2003); Ali et al. (2007)
Haemodynamic 2	Increase in arterial inflow ➔ Increase in microcirculation ➔ Increase in oxygen supply ➔ Increase in tissue oxygenation	Agu et al. (2004); Bochmann et al. (2005)
Haemodynamic 3	Increase in lymphatic outflow/function ➔ Decreased muscle swelling and oedema ➔ Decrease in pain and muscle damage markers	Kraemer et al. (2001); Davies et al. (2009)
Mechanical	Decrease in muscle oscillation ➔ Decrease in muscle fibre recruitment ➔ Decrease in energy cost ➔ Increase in movement economy and decrease in fatigue	Kraemer et al. (1998); Bringard et al. (2006)
Neuromuscular	Triggering capsular, cutaneous and muscular receptors ➔ Decrease in presynaptic inhibition ➔ Increase in proprioceptive feedback ➔ Increase in coordinative function	Doan et al. (2003); Bernhardt and Anderson (2005)
Thermal	Decrease in skin blood flow ➔ Decrease in sweat evaporation ➔ Increase in muscle temperature	Doan et al. (2003); Duffield et al. (2010)
Psychological	Decrease in pain perception ➔ Increase in vitality (Placebo?)	Kraemer et al. (1998); Ali et al. (2007); Duffield and Portus (2007)

Haemodynamic/Cardiodynamic effects

Haemodynamic effects of SCGs are the compression effects that are best understood as they are most widely covered in literature due to the medical origin of CGs as a treatment for venous disorders. Compression is believed to increase blood flow by improving the venous valve function caused by a reduction of the vein diameter (MacRae et al., 2011; ÖKO-TEST, 2015). However, it needs to be considered that compression in the medical field works, as it is applied to patients with dysfunctioning venous valves. It has been questioned whether the effect of improved venous return could also be observed in healthy athletes. When standing, it is more difficult to enhance blood flow velocity due to increased venous pressure (MacRae et al., 2011). Even if SCGs decrease artery diameters, faster blood flow does not necessarily equate to more blood flow volume per unit time, i.e. venous return (MacRae et al., 2011). During exercise, especially endurance exercise, there are increasing demands on the cardiodynamic system to provide adequate cardiac output and venous return (Couturier and Duffield, 2013). Compression is believed to balance transmural pressure (the difference between intra- and extravascular pressure) (Couturier and Duffield, 2013). Whilst Zaleski et al. (2015) have shown that compression socks can reduce haemostatic activation in marathon runners, other studies have been inconclusive (Born et al., 2014).

SCGs had little effect on participants' heart rates during various exercise protocols (e.g. Bringard et al., 2006; Ali et al., 2007; Duffield and Portus, 2007; Duffield et al., 2008; Higgins et al., 2009; Houghton et al., 2009). A slower heart rate is the result of increased heart stroke volume caused by the enhanced venous return (Born et al., 2014), thus it is unclear if SCGs have significant effects on venous return of healthy athletes during exercise.

Mechanical effects

The mechanical effects of wearing SCGs are mainly based on the notion of providing support to the soft tissue and reducing muscle vibration. When muscles oscillate, fibre recruitment increases as muscles attempt to dampen the oscillation (Wakeling et al., 2013), which increases energy expenditure. Reducing muscle vibration thus could result in longer time to fatigue (Born et al., 2013). It has further been suggested that compression reduces the physical space for soft tissue to swell or haemorrhage (French et al., 2008) and that reduction of muscle vibration could minimise structural muscle damage, resulting in reduced DOMS (Ali et al., 2007).

Neuromuscular effects

Whilst SCG brands claim that compression improves proprioception and some researchers (e.g. Doan et al., 2003; Bernhardt and Anderson, 2005) support the notion from a scientific standpoint, there is little evidence to prove this claim. With only limited existing research measuring neuromuscular effects of SCGs, sound evidence is lacking. Kraemer and colleagues (1998) reported enhanced proprioception resulting in enhanced joint position sense of the hip, which resulted in improved power endurance during repetitive jumps. Duffield and Portus (2007) found no effects of three different whole-body compression garments on the throwing accuracy of cricketers. Lee and colleagues (2017) measured brain waves during side-step tests to assess agility. They concluded that compression affects the nervous system increasing agility through enhanced motor-related information processing and focus on performance.

Proprioceptive effects are difficult to measure due to the complexity of muscle receptors engaging in proprioception (Bernhardt and Anderson, 2005), the potential subtlety of effects (Hooper et al., 2015) and likely interrelations of different compression effects.

Thermal effects

There is mixed evidence on thermal effects of SCGs. Whilst it would be logical that muscle temperature increases due to the haemodynamic effect of reduced skin surface blood flow and increased deep vein blood flow (Couturier and Duffield, 2013), there is no evidence for a reduction in skin temperature. Skin temperature increased in several (Duffield and Portus, 2007; Houghton et al., 2009; MacRae et al., 2012; Venckunas et al., 2014; Priego Quesada, Lucas-Cuevas, Gil-Calvo, et al., 2015), but not all (Leoz-Abaurrea, Tam, et al., 2016) studies using a variety of exercise protocols, however core temperature was not affected. This could lead to faster onset of fatigue, as Phillips (2015) suggested that skin temperature could have a higher impact on fatigue than core temperature during prolonged submaximal exercise (moderate intensity at 30-180min).

Psychological effects

It is likely that SCGs have a psychological effect on wearers. However, it is difficult to measure and the extent to which certain positive effects of SCGs found in literature are based on a placebo effect is unknown.

2.6.1.4 Problems with Measuring Effects of Sports Compression Garments

The main problem with trying to quantify the effects of SCGs on exercise performance and recovery is the difficulty to eliminate a potential placebo effect. A sensation of vitality can significantly affect exercise performance and feelings of exertion. SCGs can therefore act as an ergogenic aid even in the absence of any physiological effects (Born et al., 2013). If a positive mechanical or physiological effect is found, it is unclear what the underlying mechanism was that caused this effect. As it is unlikely that participants can be fully blinded due to the obvious difference in tightness of compression and placebo garments (MacRae et al., 2011), participants' beliefs in the functionality of SCGs and previous experience with SCGs could be recorded via a questionnaire, as was done by Stickford et al. (2015). There is limited research that explores users' perceptions and attitudes towards SCGs. In addition, a lack of understanding of the mechanisms responsible for the beneficial effects of SCGs adds to the ambiguity of current research and leads to conflicting interpretations of data.

Studies measuring the effects of SCGs on recovery often use perceived muscle soreness as an indicator of the severity of DOMS rather than using blood markers that could indicate the extent of muscle damage. It would be useful to measure both perceptual and objective measurements in order to get an indication of what the underlying mechanisms of the observed effects are (e.g. improved venous return or psychological effect). It is complex to assess SCG functionality, as effects could be caused by garment characteristics other than compression (e.g. thermal or ergonomic comfort) (Gupta, 2011). Whilst it may suffice wearers to know whether SCGs can have a positive effect on their exercise performance and/or recovery, researchers should strive to understand the underlying mechanisms responsible for the effects. Once researchers have a better understanding of these aspects, standardised test methods and parameters for the evaluation of the effects of SCGs can be defined and SCGs can be designed in a targeted manner to optimise the desired effect.

2.6.2 Studies Measuring Effects of Sports Compression Garments

There has been a strong increase in research studies on SCGs over the past 15 years with the majority of studies conducted by researchers from sports science fields (Fu et al., 2013). In order to get a better idea of whether there is robust evidence of SCGs improving performance and recovery of healthy athletes, existing studies evaluating the effects of SCGs on exercise performance, post-exercise recovery and proprioception of healthy sportspersons were analysed (see section 4.4.2 for literature search strategy and inclusion criteria). 146 studies were included in the analysis, a list of which can be found in Appendix B. The extensive list of existing studies was divided into studies measuring effects on exercise performance and post-exercise recovery, as the mechanisms for improved performance and recovery are likely to vary. Studies only measuring effects on kinematics and/or proprioception were separated into an additional category. All studies were further categorised into garment types and the main type of exercise (endurance, strength or power) used in the experimental protocol to get an overview of existing research (refer Appendix B). Different garments and levels of body coverage affect different muscle groups and are, therefore, non-comparable. The same is true for different exercise types utilising different metabolic systems.

Areas of research that received the most attention were the effectiveness of below-knee compression socks and full-length compression tights on performance when worn during endurance running and cycling exercise tests. More studies focused on performance than recovery effects.

2.6.2.1 Pressure Levels Reported in Existing Research

One of the main concerns with existing studies on the functionality of SCGs is that most researchers did not measure the pressures exerted by the SCGs under investigation. Out of 146 analysed studies 50 studies did not report any pressure levels at all, 49 studies reported the estimated pressure levels provided by the SCG brands, whilst only 37 studies measured compression in vivo using PM devices (see Appendix C). There were 4 studies that measured compression in vitro, 2 studies not reporting pressure values, but stating that pressures were measured and 4 studies that calculated compression using mathematical formulas. According to Laplace's Law, the bigger the radius of the object receiving tension, for instance a leg, the lower the pressure applied by the same amount of tension (refer section 2.5.3). With compression tights mostly being fitted based on height and weight measurements, there could be a wide range of pressures exerted among participants of studies that report estimated pressures due to different limb girths and tissue composition (MacRae et al., 2011; Hill et al., 2015). Hence, there is a possibility that studies that did not measure pressures and concluded that SCGs do not provide any benefits to athletes, did not have sufficient pressure applied to participants' bodies (Brophy-Williams et al., 2015). However, there is no recognisable trend in levels of pressure measured in existing studies that lead to positive results for performance or recovery over other pressure levels as is shown by the pressure ranges in Table 2.6 (also refer to

Appendix C). There are vast variations in pressure levels across studies. Pressure ranges resulting in positive effects and no effects clearly overlap. At the calf, for example, positive performance effects have been reported for pressures between 7 and 40mmHg, whilst other studies have demonstrated no effects on performance with pressure levels of 8 to 40mmHg.

Table 2.6: Pressure ranges of lower body SCGs measured in reviewed existing research

		Performance	Recovery
Ankle	Positive effect	8-18 mmHg	6-22 mmHg
	No effect	9-46 mmHg	10-26 mmHg
Calf	Positive effect	7-40 mmHg	7-24 mmHg
	No effect	8-40 mmHg	8-17 mmHg
Thigh	Positive effect	5-34 mmHg	5-23 mmHg
	No effect	7-18 mmHg	7-37 mmHg

It is generally believed that the levels of pressure applied by SCGs are lower than pressure levels of MCS, however a number of studies reported applied pressures as high as 40mmHg at the ankle (Sperlich, Haegele, et al., 2011; Wahl et al., 2012), which would be compression class III (strong compression) in most MCS standards (refer Table 2.1), generally used for severe lymphedema and leg ulcers.

Both progressive (e.g. Trenell et al., 2006; Hill, Howatson, van Someren, Walshe, et al., 2014) and degressive (e.g. Maton et al., 2006; Ali et al., 2010; Lovell et al., 2011; Pruscino et al., 2013) pressure profiles have been used for lower body SCGs in the reviewed studies with mixed results on sports performance and/or recovery.

Pressure levels of upper body SCGs were lower than pressure levels of lower body SCGs (refer Appendix C) with applied pressure on the arms ranging from 7 to 21mmHg at the forearm and 3 to 14mmHg at the upper arm in the studies examined, which would be classified as very mild to mild compression in the medical sector (according to EU pre-standard). This pressure range has shown both positive and no effects on performance and recovery. Reported pressure levels at the torso were comparatively low ranging from 1 to 9mmHg.

It is essential that future studies report pressure levels measured in vivo using a reliable PM device to enable interpretation of the research and to develop a better understanding of required pressure levels and effects of wearing SCGs (Brophy-

Williams et al., 2014; Tyler, 2015; MacRae et al., 2016). Pressure should be understood as the ‘dosage’ of compression treatment, which is a critical variable that needs to be reported in the same way as the dosage of, for instance, nutritional supplements would be reported.

2.6.2.2 Effects on Exercise Performance

Out of the 146 studies analysed, MacRae et al. (2012) and Sear et al. (2010) were the only researchers assessing the effects of whole body compression on sports performance. Both studies used Skins long tights and long sleeved tops and fitted the garments according to the Skins size chart, but did not report how well the garments fitted participants. MacRae and colleagues’ (2012) experimental protocol was based on endurance cycling of twelve male recreational athletes, whilst Sear and colleagues (2010) investigated high-intensity interval running of eight competitive athletes. There were no positive effects on performance for participants in the cycling study, whilst there were some positive effects on distance covered, speed and tissue oxygenation in the running study.

The majority of the analysed studies tested the functionality of compression tights and socks. With the study’s focus on whole-body SCGs, tights were of more relevance to this study and were consequently analysed more closely. However, when only including studies that measured in vivo pressures, only eight studies assessing the effects of full-length compression tights on exercise performance remained (see Appendix Table D-1). These studies measured different variables to come to their conclusion of whether or not the compression tights under investigation provided a benefit to the subjects’ performance, which flags the question of comparability of these studies. Six of the studies applied an endurance exercise protocol, whilst two (Faulkner et al., 2013; Born et al., 2014) used a power-focused sprint protocol. Half of the studies (Scanlan et al., 2008; Dascombe et al., 2011; Goh et al., 2011; Faulkner et al., 2013) used compression tights from the brand Skins and stated that the brand’s size chart was used to fit the compression tights. Mean pressure levels applied to the participants in the four studies varied (calf: 13-19mmHg; mid-thigh: 7-14mmHg) and so did the effects on performance, which is unsurprising due to the heterogeneity of the study designs.

Barwood et al. (2013) lack a description of the garment type used in the study, however it can be assumed from their description of PMs, that they used tights. It is critical that researchers focus more on the SCG and describe at least the basic characteristics of the garments (type, body coverage, brand) and the way they were fitted. Any obvious fit issues of the garments should also be reported, as these could affect reproducibility of studies.

Both Barwood (2013) and Goh (2011) assessed the effects of wearing compression tights in hot environments and reported neither positive nor adverse effects. Born and colleagues (2014) were the only researchers finding significant positive effects on performance measures. They concluded that the benefits were likely caused by altered running mechanics rather than haemodynamic effects. Conversely, Dascombe et al. (2011) and Scanlan et al. (2008) found no significant effects on performance when wearing SCGs during endurance running and cycling, despite recording some positive physiological effects on muscle blood flow and oxygenation. Faulkner et al. (2013) reported significant positive effects on perceived exertion, which was, however, not translated into improved performance.

More studies on the effects of upper body SCGs (tops and arm sleeves) are needed, as this area is lacking quality research studies. The only two studies (Sperlich et al., 2014; Leoz-Abaurrea, Santos-Concejero, et al., 2016) identified measuring compression of upper body SCGs did not find any positive effects on performance.

2.6.2.3 Effects on Post-Exercise Recovery

Researchers have suggested that there is more evidence for beneficial effects of SCGs on recovery than on performance (Perrey, 2008; Beliard et al., 2015; Engel et al., 2016). However, when looking at studies measuring the effects of SCGs on post-exercise recovery, it becomes clear that their study designs vary even more than studies focusing on performance effects. There are particularly big differences between wear times. It is currently not clear when (i.e. during exercise, after exercise or both) and for what length of time (e.g. 12h, 24h, 48h) SCGs should be worn for optimal recovery, however, wear time in current studies varies widely from 30 minutes to 120 hours. Recovery is usually assessed by measuring and comparing pre- and post-fatiguing exercise performance (muscular strength or power) and comparing results to baseline or assessing the level of DOMS. Blood markers, such as creatine kinase and lactate are used as indicators of recovery, however opinions diverge on their validity (refer Barnett, 2006). Further, the reliability of time-to-exhaustion tests to assess the functionality of SCGs has been questioned, as it is susceptible to the placebo effect (Born et al., 2013).

Training status of participants is important when measuring recovery-related effects, as exercise-induced muscle damage is likely to be more severe in untrained athletes due to habituation and the repeated bout effect (Barnett, 2006; MacRae et al., 2011). Also exercise type, duration and intensity largely affect muscle damage and DOMS (Connolly et al., 2003). Further, levels and synthesis of lactate and H+ can vary significantly among team game-, endurance- and sprint-trained athletes (Phillips, 2015).

Several researchers (Gill et al., 2006; French et al., 2008; Montgomery, Pyne, Hopkins, et al., 2008) compared the use of SCGs to other recovery modalities (e.g. contrast bathing, cold water immersion, active recovery) and concluded that SCGs had no or little positive effects on recovery and were only superior to passive recovery. However, none of the studies measured compression levels.

Only one study (Piras and Gatta, 2017) measured the effects of whole body SCGs on post-exercise recovery. The researchers reported positive effects on recovery with a whole body suit worn for 90 minutes after a 400-m freestyle swimming protocol.

When analysing the effects of wearing full-length compression tights on recovery, eleven studies could be identified that measured pressure levels. Out of these studies, summarised in Appendix Table D-2, nine study designs were based on wearing compression tights post-exercise (24-72h) and two during exercise. Whilst the studies varied substantially in design and measured variables (second performance measurements, blood markers, perceived muscle pain), all studies found at least some effects that could positively affect post-exercise recovery. Some researchers found improvements in subsequent endurance performance (De Glanville and Hamlin, 2012; Hamlin et al., 2012), others only found improved subjective perceptions of recovery (Pruscino et al., 2013; Hill, Howatson, van Someren, Walshe, et al., 2014). None of the studies reported if garment fit was adequate. However, DeGlanville and Hamlin (2012) provided a photo in their publication, in which fabric folds are visible in the ankle area, meaning the garment would not apply the desired pressure level to the ankle.

Whilst no general conclusions on the functionality of SCGs can be drawn from the studies presented in Appendix D due to the heterogeneity and small scale of the studies, a tendency to positive effects of compression tights on recovery can be observed from the conclusions of the studies, whilst effects on performance are mixed. As many of the studies reporting positive effects on recovery measured perceived recovery and some found only perceptual effects, but not physiological effects, there is a possibility that the reason for more ‘evidence’ in the recovery-enhancing properties of SCGs compared to performance-enhancing properties is grounded in a placebo effect of SCGs.

Some SCGs claim that SCGs prevent injuries, however, limited research exists to support this claim. Ménétrier (2014) conducted a survey with 203 trail runners and compared their self-reported injuries to their training levels and use of SCGs. Their preliminary findings indicated a trend towards fewer injuries with the use of SCGs during and after exercise. However, further long-term studies are required to confirm this.

It is impossible to judge whether SCGs have a positive effect on sports performance or recovery when the underlying mechanisms are not understood. Whilst it is currently unclear if SCGs have any general beneficial effects on exercise performance or recovery, it seems that wearing SCGs during or after exercise has no significant detrimental effects.

It needs to be considered that results of no effects of SCGs with one sample could result in positive effects with another sample of different training status, but also with a similar sample due to potential subjective perceptual effects. Hence, it would be useful to conduct studies with larger sample sizes and a variety of different training statuses for various exercise types. These studies should also measure perceptual effects in addition to objective performance markers. It shows that even though a wealth of research on SCGs has emerged over the past 15 years, the interdisciplinarity of the subject and complexity of the relationship between SCGs and the human body mean that the research field is still in its infancy.

2.6.2.4 Problems with Existing Research

In recent years, a number of descriptive (Perrey, 2008; MacRae et al., 2011; Sperlich, Born, et al., 2011; Fu et al., 2013; Beliard et al., 2015) and statistical (Born et al., 2013; Hill, Howatson, van Someren, Leeder and Pedlar, 2014; Marques-Jimenez et al., 2016; Brown et al., 2017) review studies have been published in an attempt to shed light on the confusing findings of studies investigating the effects of SCGs. Most authors state the problem of heterogeneity of the studies, yet many attempt to draw general conclusions from the summarised studies without distinguishing between different exercise and garment types. This is especially problematic when conducting meta-analyses. Most studies on the effects of SCGs have a small sample size. As a result, generalisations cannot be made from examining individual studies. Meta-analyses are a meaningful way of comparing a number of smaller studies by analysing their effect sizes. However, it is critical to be cautious of the origin of the different effect sizes when combining them. Unless the study designs are similar in terms of instruments and population, meta-analyses lose their value (refer Coe, 2002). Different exercise types use different energy systems and muscles (refer Appendix A), thus they have fundamentally different effects on the human body. Also, the location of pressure application (full body, full leg, thighs only, calves only, etc.) and time of application is likely to influence the effects of SCGs. With many study designs being fuzzy in various respects (e.g. allocation and randomization, garment types and fit on body) and not measuring compression, drawing conclusions in meta-analyses based on these studies further adds to the confusion of SCG research.

The descriptive literature review of MacRae and colleagues (2011) provides a comprehensive overview of the state of research on the effectiveness of SCGs. The study, however, lacks a description of the methodology (e.g. inclusion/exclusion criteria of studies) and evaluates studies not reporting pressure levels. It is, nevertheless, the only study that highlights the importance of garment characteristics. The authors provide valuable recommendations for future research. However, with research mainly conducted in the fields of physiology, biochemistry, biomechanics and sports medicine (Fu et al., 2013), considerations of garment aspects (e.g. fabric properties, garment design and construction) have widely been neglected. Researchers have, for instance, neglected the influence that garment construction (e.g. seams) and fit have on pressure delivery. Existing studies do not comment on the fit of SCGs worn by participants and only few researchers report the fitting methodology (e.g. using manufacturer's size chart). There is also a lack of research on the behaviour of pressure levels of SCGs during prolonged and repeated wear and over a garment's life. SCGs undergo various stresses by being exposed to mechanical forces during donning, wear and laundering as well as chemicals, such as deodorant, body lotions, perspiration and laundry detergents (MacRae et al., 2016). Any change to the fabric structure (e.g. residual extension) could lead to changes in pressure delivery.

Beliard and colleagues (2015) highlighted that there are likely differences between male and female participants, endurance and resistance exercise and recovery in terms of pressure application and required pressure levels due to variations in body tissue composition and physiological functions. The researchers concluded that there is no relation between the effects of SCGs and the applied pressure levels based on the fact that the examined studies found positive and negative compression effects with both low and high pressures. This conclusion oversimplifies the complexity of factors that could influence garment pressures and participants' performance. As the studies analysed varied substantially in design (e.g. wear time 15 minutes to 48 hours), general conclusion should be drawn with caution.

Review studies mixing results of studies testing different garments of substantially different levels of body coverage (tops, tights, stockings, shorts, socks, whole-body compression), different genders and training statuses of participants plus including studies without any pressure indications, yet utilising effect sizes (e.g. Born et al., 2013; Hill, Howatson, van Someren, Leeder and Pedlar, 2014), are problematic. The fact that different review studies differ in their conclusions is testament to the complexity of interpreting data and questions the reliability of drawing general conclusions from the review of existing studies on the functionality of SCGs.

2.7 Chapter Conclusions

A critical analysis of the wealth of research studies investigating the functionality of SCGs found that the majority fail to measure pressure levels applied by SCGs. Furthermore, they do not consider the effects that garment design and fit could have on functionality. This creates ambiguity in the research field of SCGs inhibiting reliable judgements about the functionality of SCGs. The discussed problems with existing SCG research can be summarised as follows:

- Study designs are often fuzzy with important factors, such as level of applied compression, garment characteristics, fit and size frequently not reported.
- The majority of studies do not measure pressures exerted by SCGs.
- Studies that measure compression often do not consider the pressure profile across the wearers' bodies, yet often make assumptions on whether the pressure profile is degressive or progressive.
- Types of measurements taken to assess performance/recovery and their interpretation vary among studies.
- The heterogeneity of studies causes mixed results and inhibits meaningful comparisons:
    - Heterogeneity of participants (sex, age, level of training, familiarity with exercise protocol, BMI, muscle mass, body surface tissue composition)
    - Heterogeneity of exercise protocol (type of exercise (e.g. endurance vs. resistance), intensity and duration of exercise, time of test, environmental conditions)
    - Heterogeneity of SCG intervention (garment type/body coverage, wear time, wear duration, garment design (e.g. fabric, seams, special features), levels of pressure applied by SCGs)
    - Heterogeneity of measuring effects of SCGs (performance and recovery variable measured, interpretation of data)
- Because of the diversity of studies and small sample sizes, there is not enough research to make reliable judgements about SCGs (even though some authors draw conclusions from results of very heterogeneous studies).
- Some studies use 'placebo garments' to account for a potential placebo effect of SCGs. It is doubtful that participants can be fully blinded, therefore a placebo effect cannot be discounted.
- Considerations of SCG users' perceptions and attitudes towards SCGs have been neglected.

- Considerations of the relationship of garment aspects (e.g. sizing systems, garment fit, fabrics) that could affect functionality of SCGs have been disregarded.
- No attention has been paid to considerations of the whole complexity of SCGs, such as the relationships between applied pressure, body dimensions, movement and garment characteristics.

Many of these problems can be associated with a lack of understanding of how SCGs behave on wearers' bodies as well as uncertainties about the underlying mechanisms of SCGs.

Even though there is an abundance of research on the effects of SCGs on performance and recovery, the diversity of research means that when broken down into the individual components, there is not enough research available that can unequivocally prove that SCGs are an effective means to enhance performance and/or recovery. More studies with the same, improved study design and garments and larger, homogenous sample sizes are required to be able to make a reliable judgement. A more standardised approach to the performance testing of SCGs with clear study designs is needed including a more detailed focus on the intervention: the SCG used and its properties and applied pressures. SCGs and participants should be described in detail. As a placebo effect cannot be discounted, studies should pay more attention to perceptual effects of SCGs and consider participants' attitudes and opinions towards SCGs.

Inconsistencies with pressure levels and pressure distribution and varied reports of benefits across different studies and individuals indicate that compression exerted by SCGs is currently not well controlled. There seem to be misconceptions among researchers and a lack of understanding of the complex interactions of SCGs with the human body and the environment and their effects on compression.

3 DESIGN OF SPORTS COMPRESSION GARMENTS

3.1 Chapter Introduction

With most studies on compression garments (CGs) conducted by researchers from the sports science and medical fields, considerations of garment aspects have been neglected. This chapter provides an overview of the design of sports compression garments (SCGs) by addressing SCGs from a functional clothing design (FCD) perspective.

With currently no known studies on the sizing, grading and construction of SCGs alongside limited research on fabric properties of SCGs, this chapter provides essential information for the design of SCGs. The technical design of clothing is a very specialised field that requires a comprehensive understanding of anthropometrics, pattern design, fabric properties and garment construction techniques (Power, 2013). The chapter aims to provide the reader with this knowledge in relation to SCGs, whilst highlighting the importance of the relationship between the human body and SCGs. In addition, ways of predicting pressures when designing SCGs are discussed. This knowledge is essential to define a framework for the design development of SCGs later on in the study.

3.2 Functional Clothing Design

3.2.1 Introduction to Functional Clothing Design

Functional clothes are worn for specific functional needs, such as performance improvement or protection from the environment. Designers have to integrate these functional needs into the clothing system (Suh et al., 2010; Gupta, 2011). The design of functional clothing differs from general clothing design as functionality is a primary concern and the user is at the centre of the design process with critical decisions being made in the initial research phase rather than later in the design phase (Suh et al., 2010). As such, FCD is comparable more to graphic, product or industrial design than fashion design.

FCD is a multi-faceted, interdisciplinary activity combining a wide array of disciplines including design, science, technology, sociology, psychology and business, combining creativity and intuitive fashion methods with technical understanding and engineering processes (McCann, 2005; Gupta, 2011; Watkins and Dunne, 2015; Romeo and Lee, 2016)

Functional clothing generally addresses function (e.g. fit, comfort, protection) before aesthetics (Watkins and Dunne, 2015), however, it is nevertheless important to consider symbolic values and needs (Rosenblad-Wallin, 1985). Symbolic needs are concerned with the impression the wearer gives to others (e.g. respectability, group identity), so psychological and social factors are critical (LaBat, 2006; Gupta, 2011). A garment that functions perfectly could be rejected by users if it is not in tune with their symbolic needs (Gupta, 2011). In some sports disciplines aesthetic garment characteristics are more important than in others (e.g. golf (Wheat and Dickson, 1999) or cycling (Casselman-Dickson and Damhorst, 1993a)).

FCD utilises user-centred design approaches, as functional clothing is supposed to enhance human performance (Suh et al., 2010; Watkins and Dunne, 2015). User-centred design, also known as human centred design (Norman, 2013), was first coined in the 1980s (Norman and Draper, 1986). In his seminal work, Norman (2013:8) described human centred design as “an approach that puts human needs, capabilities, and behavio[u]r first, then designs to accommodate those needs, capabilities, and ways of behaving”. User-centred design requires a detailed analysis of users and use-situations to identify user needs, which are then translated into design criteria (Rosenblad-Wallin, 1985; Suh et al., 2010). Whilst in general clothing development the focus lies on the physical aspects of a product (e.g. style, colour), the focus in FCD lies on the user and the relation between the user and the garment (Rosenblad-Wallin, 1985).

Functional requirements for sportswear generally include optimal thermal, tactile and ergonomic comfort as well as any protection required (e.g. bacterial, UV, impact). The main functional need of SCGs is to enhance wearers’ sports performance and recovery through pressure application.

3.2.2 Functional Clothing Design Frameworks

FCD needs to fulfil the users' requirements and, therefore, requires a structured approach to firstly identify user needs and then translate these into garment characteristics to obtain a finished product that fulfils the identified user needs. Engineering design processes lend themselves to such a systematic approach. Over the years, a number of frameworks for the design of functional clothing have been suggested, which are indirectly based on engineering design processes (Regan et al., 1998).

3.2.2.1 Design Processes

Table 3.1 summarises the key stages of the proposed design frameworks and provides examples of their application in FCD research. The processes are based on the notion of problem-solving (Koberg and Bagnall, 1981), working through a series of stages to work from the initial problem to the final garment. The design processes are presented in subsequent stages, however they do not necessarily follow a linear fashion; designers may iterate stages (Watkins, 1995). The different processes are similar, but vary in the number of stages included in the process. All processes emphasise the need for research at the onset of the design phase in order to frame the users' exact needs. This is done through various methods of interaction with the end users including surveys, interviews, focus groups and observations in addition to reviewing relevant literature and analysing the market to get a good understanding of the design conditions prior to commencing design tasks (LaBat and Sokolowski, 1999; Tullio-Pow, 2016; Morris et al., 2017; Ledbury, 2018). Rosenblad-Wallin (1985) emphasised the focus on the determination of user needs and the requirements of the use situation. The researcher's distinction between functional and symbolic user needs was further developed by Lamb and Kallal (1992) in their FEA (Functional, Expressive, Aesthetic) Consumer Needs Model that will be discussed in the next section. They integrated the model into a slightly amended version of Watkins (1995) seven-stage design process, a well established process further strengthened by the enhanced focus on users (Bye and Hakala, 2005).

Following the initial research and problem definition stages, the design processes involve idea generation activities, followed by development and evaluation of the most promising design ideas and finally the implementation. LaBat and Sokolowski (1999) established that the major stages of the functional clothing and engineering design processes could be reduced to three key elements: Problem definition and research, creative explorations and implementation of the design. The evaluation stage is viewed as critical because of the complex interactions of the designed garment with the user's body and environment, which cannot be fully predicted. Due to this complexity the most detailed information come from testing garments in wear trials (Watkins, 1995). This is especially true for SCGs, where compression needs to be evaluated on the wearers' bodies. Recently, Watkins and Dunne (2015) reduced the established Watkins seven-stage process to five essential stages for the design of functional clothing: Research, problem definition, ideation, development and evaluation.

Table 3.1: Overview of functional design processes and example studies applying the processes

<table>
<tr><th></th><th>Nine-stage design process</th><th colspan="2">Seven-stage design process</th><th>FEA model</th><th>Five-stage design process</th><th>Three-stage design process</th><th>Activities involved</th></tr>
<tr><td rowspan="8">Stages</td><td>1. Problem identification</td><td>1. Request made</td><td>1. Accept</td><td rowspan="5">1. Problem identification</td><td rowspan="2">1. Conducting research</td><td rowspan="6">1. Problem definition and research</td><td rowspan="6">• Literature review,
• Market analysis,
• Observation,
• Interviews,
• Focus groups,
• Questionnaires
• Experimentation,
• Activity and movement assessment,
• Environmental assessment,
• Social-psychological assessment
• Creating personas for user groups,
• Identifying design variables,
• Identifying constraints,
• Developing frameworks,
• Identifying design requirements/criteria</td></tr>
<tr><td>2. Problem analysis</td><td>2. Research – Design situation explored</td><td>2. Analyse</td></tr>
<tr><td>3. Objective set-up</td><td>3. Research – Problem structure perceived</td><td rowspan="4">3. Define</td><td rowspan="4">2. Defining the problem</td></tr>
<tr><td>4. Demand formulation</td><td>4. Specifications described</td></tr>
<tr><td>5. Data analysis</td><td rowspan="2">5. Design criteria established</td></tr>
<tr><td>6. Demand specification</td><td>2. Preliminary ideas</td></tr>
<tr><td rowspan="2">7. Idea development/ Technical solution</td><td rowspan="2">6. Prototype developed</td><td rowspan="2">4. Ideate</td><td>3. Design refinement</td><td>3. Generating ideas</td><td rowspan="2">2. Creative exploration</td><td rowspan="2">• Brainstorming,
• Lateral thinking,
• Mind mapping,
• Interaction matrixes,
• Sketching
• Materials testing,
• Materials selection,
• Pattern development,
• Construction methods,
• Finishing techniques</td></tr>
<tr><td>4. Prototype development</td><td>4. Developing designs</td></tr>
</table>

<table>
<tr><th></th><th>Nine-stage design process</th><th colspan="2">Seven-stage design process</th><th>FEA model</th><th>Five-stage design process</th><th>Three-stage design process</th><th>Activities involved</th></tr>
<tr><td rowspan="3"></td><td>8. Evaluation/ Modification/ Selection of prototype</td><td rowspan="3">7. Design evaluation</td><td>5. Select</td><td>5. Evaluation</td><td rowspan="3">5. Evaluating designs</td><td rowspan="3">3. Implementation</td><td rowspan="3">• Checking specifications against objectives,
• Reassessing critical factors,
• Ranking and weighing,
• Using decision matrixes
• User and wearer acceptability testing:
  • Interviews,
  • Focus groups,
  • Questionnaires.
• Fit evaluation and functional effectiveness testing:
  • Lab testing,
  • Field testing.</td></tr>
<tr><td rowspan="2">9. Evaluation of final solution</td><td>6. Implement</td><td rowspan="2">6. Implementation</td></tr>
<tr><td>7. Evaluate</td></tr>
<tr><td>Authors</td><td>Rosenblad-Wallin (1985)</td><td>Dejonge in Watkins (1984)</td><td>Watkins (1995)</td><td>Lamb and Kallal (1992)</td><td>Watkins and Dunne (2015)</td><td>LaBat and Sokolowski (1999)</td><td></td></tr>
<tr><td>Studies applying process</td><td>Zhang (2004) – Design of activewear for older women</td><td>Huck and Kim (1997) – Design of coveralls for grass fire fighters</td><td>Ledbury (2009) – Design of women’s outdoor clothing</td><td>Bye and Hakala (2005) – Design of women’s sail clothing</td><td>No known studies</td><td>Ho and Au (2017) – Design of racing singlet for rowers</td><td></td></tr>
</table>

3.2.2.2 Conceptualising Design Requirements

As highlighted in the previous section, the concept of FCD emphasises the analysis of user needs. There are a number of models and methods that can support designers in translating the identified needs into design requirements. The FEA Consumer Needs Model (Figure 3.1) is the most prominent model for identifying user needs.

The FEA Consumer Needs Model was developed by Lamb and Kallal (1992) as a teaching tool for fashion design students to facilitate the design research and evaluation phases. The FEA model features the 'target consumer' at the centre surrounded by 'culture', which affects users' clothing choices (Kaiser, 1997). The user demands on the garment are divided into three, non-mutually exclusive categories: functional (utility), expressive (communicative and symbolic aspects), and aesthetic (desire for beauty) considerations (Lamb and Kallal, 1992). The three different needs vary for different target consumers and need to be considered for all functional clothing developments (Suh et al., 2010).

Figure 3.1: The FEA (Functional, Expressive, Aesthetic) Consumer Needs Model developed by Lamb and Kallal (1992:42)

The FEA model has been widely applied and cited globally in functional clothing design studies (e.g. Bye and Hakala, 2005). It has been further developed (Kallal et al., 2002) as well as adapted by researchers for the design of hospital garments (Park, 2014) and clothing for disabled adolescent girls (Stokes and Black, 2012). Chae and Schofield-Tomschin (2010) added a third component to the FEA model:

regulatory requirements, resulting in the 'FEAR model' for the design of snowboard helmets.

The main merit of the FEA model lies in the provision of a structure for evaluating complex user needs and analysing clothing attitudes (Tullio-Pow, 2016). A similar approach was proposed by Romeo and Lee (2016) in their Apparel Needs Expectation (ANE) Model. The focus of the ANE model is on viewing the users' individual needs within the context of the bigger political, economic and corporate environment (macro forces).

Timmins and McCann (2014) presented the Design Tree Model (originally conceptualised by McCann (1999)), which suggests a systematic approach to the process of identifying user needs and turning these into design concepts and subsequently garment characteristics. The model distinguishes between form (aesthetics and culture of activity), function (demands of the body and activity) and commercial realities (product, position, price and promotion) (refer Figure 3.2).

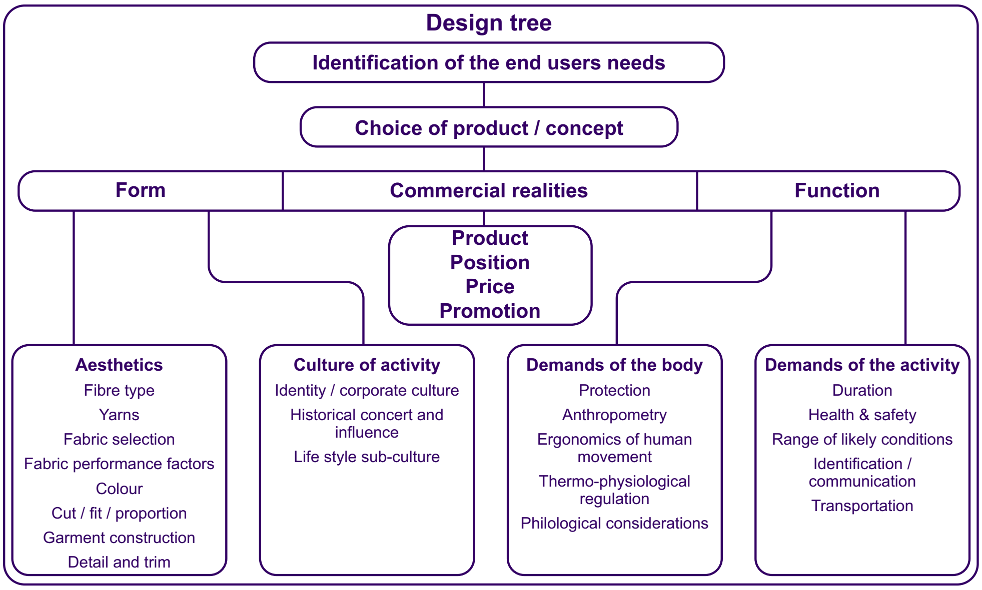


Figure 3.2: The Design Tree Model for the design of functional clothing (Timmins and McCann, 2014:197)

Power and colleagues (2016, 2017) utilised the methods of Quality Function Deployment (QFD) to translate user needs into technical requirements for medical products for children with cancer. The advantage of QFD and particularly the 'House of Quality' lies in the focus on prioritising user needs and identifying the importance of various design requirements (refer Bergquist and Abeysekera, 1996).

3.2.3 Design of Women-specific Functional Clothing

Previous research on female athletes has focused on the identity of female athletes and the paradox between the athletic role and notions of femininity (Messner, 1988; Dickson and Pollack, 2000; Hendley and Bielby, 2012). This paradox is rooted in the pressures of society to look feminine, which stopped women from participating in competitive sports, such as the Olympic Games, in the early 20th century (Warner, 1997). Contrarily, later in the 20th century, women wore masculine sportswear designed for the male figure (Fowler, 1999). Contemporary female athletes seem to embrace feminine sportswear that is fashionable, yet functional (Williams, 2010). Contemporary women's sportswear has moved away from the 'traditional' notion of women's sportswear (O'Sullivan et al., 2017), such as sports clothing in "shocking pink" or "lime green" or simply smaller versions of men's sportswear (Fowler, 1999:81).

Fowler (1999) conducted a survey to identify requirements for women's sportswear and found that both women and man prioritise comfort, quality, durability and style of sportswear, however fit is of greater importance to women than men. Other researchers have identified care, durability and quality as well as sizing and fit as sources of dissatisfaction for women's fashion clothing (Sproles and Geistfeld, 1978; Chae et al., 2006). Several studies have explored women-specific sportswear requirements for various sports disciplines, including cycling (Casselman-Dickson and Damhorst, 1993a), basketball (Feather et al., 1996), golf (Wheat and Dickson, 1999), in-line skating (Dickson and Pollack, 2000), sailing (Bye and Hakala, 2005), tennis (Chae et al., 2006) and dance (Mitchka et al., 2009). The common most important sports clothing requirements for the female participants in these studies were fit and comfort. Comfort was the most important factor for tennis clothing (Chae et al., 2006), whilst adequate fit was reported to be of the highest importance to user satisfaction for in-line skating, cycling and dance, as it supports peak physical performance (Casselman-Dickson and Damhorst, 1993a; Dickson and Pollack, 2000; Mitchka et al., 2009). Subjective fit perceptions of wearers can be influenced by the physical and psychological comfort and the appearance of the garment (LaBat and DeLong, 1990). Whilst fit and comfort appear to be the most important factors for contemporary female athletes, the definitions of comfort and fit may vary for different sports disciplines (Dickson and Pollack, 2000; Mitchka et al., 2009).

Commitment to the sport can also influence user needs and expectations on sportswear (Chae et al., 2006; Mitchka et al., 2009). Fowler (1999) suggested the differentiation between three different groups of female athletes: the serious athlete, the weekend athlete, and the women seeking comfortable apparel, all of which have different design requirements and expectations.

Expressive needs can have a larger influence on female than male athletes, as "[w]omen are more in tune with how clothes make them feel, how the woman feels in them, and whether or not it is flattering" (Weede, 1997:97). Women are further concerned about the appropriateness of their sports clothing for the specific sports discipline they participate in. They make this judgement based on the specific sporting culture and related traditions (Casselman-Dickson and Damhorst, 1993b; Bye and Hakala, 2005).

Female athletes can achieve peak performance when they are satisfied with the comfort, the performance and the appearance characteristics of their sports clothing (Wheat and Dickson, 1999). Psychological comfort can be achieved through aesthetically-pleasing (Wheat and Dickson, 1999) and well-fitting (Fowler, 1999) sportswear. However, women associate much more with clothing than the functional elements. Clothing is linked to body satisfaction (LaBat and DeLong, 1990; Littrell et al., 1990) and self-esteem (Shim and Bickle, 1994). That is why potential sculpting of the body through compressing soft tissue could be seen as a benefit of wearing SCGs by women. The psychological implications of garment fit are critical and complex (Fowler, 1999). It is vital that designers understand the multi-faceted needs of the female athletes they are designing for to optimise their performance.

3.2.4 Future Trends in Design Development

Design and product development processes are changing with powerful innovative drivers, such as digitalisation and circularity, impacting the textile and clothing industries turning them into high-tech, demand-driven and knowledge-based industries (Walter et al., 2009; Power, 2015; European Technology Platform, 2016). Among the key future trends, Industry 4.0, cross-disciplinary design teams and sustainability are likely to be the key influences for the design of functional clothing.

Industry 4.0 is a term used for the fourth industrial revolution, which involves the digitisation and automation of products and processes. For the design of functional clothing, changes in the design process are expected with the proliferation and further development of three-dimensional (3D) technologies. This includes the use of virtual fit with dynamically moving body scan avatars allowing the analysis of fabric behaviour, fit and haptic sensations to replace the production of physical prototypes (European Technology Platform, 2016; Gill, 2018) as well as automated manufacturing processes. Adidas is, for instance, building a “speedfactory” in Germany, which utilises “intelligent robotic technology” (Textiles Intelligence Limited, 2016:5). This could lead to rapid production with reduced waste and carbon footprint (European Technology Platform, 2016).

For the designer, developments in 3D computer-aided design/computer-aided manufacturing (CAD/CAM) could also lead a move away from two-dimensional (2D) patterns towards the design of 3D patterns on avatars (Gupta, 2011). The digitalisation of the pattern design and production processes in combination with 3D body scanning technologies will enable mass-customisation and e-tailoring, giving customers the opportunity to collaborate with designers in the design process (McCann, 2009b; Power, 2015). These developments will change the demands on designers and require cross-disciplinary design teams including technologists and computer scientists in order to utilise multi-disciplinary knowledge (McCann, 2005).

Sustainability and ethics in design will be a major concern and determine every design decision from material selection to end-of-life management of garments, as there is a growing awareness of the major environmental impact of clothing (McCann, 2005, 2009b). The focus has moved from trying to reduce the effects of clothing at the end of the product life (e.g. reuse, recycling) to embracing sustainability considerations as early as possible in the design phase (McCann, 2009a). However, currently sustainability does not seem to be particularly high on the agenda of SCG specialist brands, contrary to the overall sportswear industry.

3.3 Designing for the Human Body

Clothing is designed to cover the human body by placing 2D textile panels around the body and joining them together to conform to the body's silhouette (LaBat, 2006). The interaction of clothing and the human body creates a mini-environment that is personal to the wearer (Watkins, 1995). This mini-environment in combination with the interactions between a multitude of other factors, such as the size and shape of the garment and the body, the external environment and body movement, are key aspects to consider when designing for the human body, especially when designing sportswear with the intention to enhance performance (LaBat, 2006; Liu and Little, 2009). It is, therefore, critical to understand the relationship between the human body and clothing. Compared to most conventional clothing, SCGs have the particular property of having negative ease, i.e. they are smaller than the wearer's body. They are next-to-skin garments that act like a second skin, making it even more important to understand their relationship with the human body.

When designing clothing for the human body, measuring body dimensions to classify bodies into sizes is critical to achieve adequate fit of clothing (Apeagyei, 2010), but also different body shapes across a population and dimensional changes caused by the movement of the body need to be considered (Ashdown et al., 2004). The usefulness of SCGs depends on adequate pressure delivery of the garment, which can only be achieved with the correct relation between garment and body dimensions for the particular fabric used. Fit of the garment is, thus, a key consideration. There is only very limited research available on how to technically design SCGs that feature a desired pressure profile on a human body of known size.

3.3.1 Anthropometrics

Ergonomics or human factors engineering is the design of products or environments under consideration of the characteristics and demands of the human user (Pheasant, 1990). Anthropometrics is a branch of ergonomics, which incorporates the measurement of body dimensions (Pheasant, 1990). Anthropometrics is an old science with various traditions developing over time. Measurements are defined by body landmarks some of which are easier to identify (e.g. nape of the neck) than others (e.g. waist) (Beazley, 1997). Variations in landmark determination result in variations of anthropometric measurements and the inability to compare measurements. However, various national and international standards exist applying inconsistent techniques (ISAK, 2001). Age, gender and ethnicity are key aspects affecting anthropometric data (Pheasant, 1990), but also sports can affect the physical characteristics of the human body through the development of specific muscle groups. Elite athletes show fundamental differences in body dimensions compared to the average population (De Raeve and Vasile, 2016). However, there are currently no quantifications of varying body dimensions based on sports disciplines that could be applied in product development (Gill, 2015).

Anthropometrics plays an important role in clothing design, where correlations between different body dimensions are calculated to design garment patterns and sizing systems that fit the human body (Pheasant, 1990). Clothing is mostly designed based on anthropometric measurements taken in static, standing positions (LaBat, 2006). However, some body dimensions change with the movement of the body, for instance length measurements when a joint is flexed. Clothing needs to accommodate these changes to allow freedom of movement and avoid both bunching up of excess material and tightness of garments (Chi and Kennon, 2006; LaBat, 2006; Watkins and Dunne, 2015). As highlighted in Appendix A, the nature of the human body is complex with muscles of diverse shapes and joints with varying degrees of freedom resulting in skin deformations in different directions, especially movements of the arms and legs. These changes during movement lead to extension or contraction of the body's skin and body surface. This has a direct effect on garment fit and comfort and is of particular importance in sportswear. For optimal comfort and freedom of movement, the garments should behave like a second skin following the same extension and contraction pattern as the wearer's body (Watkins and Dunne, 2015). Due to the varying movement requirements for different sporting disciplines, performance sportswear should be adapted to the particular activity and specific postures of the sport (Lectra, 2015).

Kinanthropometry is a development of anthropometrics dealing with the measurement of human movement and the related variations of the body in the context of sport (Kerr et al., 1995). Kirk and Ibraham (1966) were the first researchers to quantify variations in length based on flexion of the leg using manual measurements. In addition to traditional measurement methods, videos or photographs of users in different movements can be analysed in order to identify the range of motion required for the particular exercise as has been done in existing research (Watkins, 1977; Ashdown, 1998). More recently, 3D body scanning (refer Figure 3.3) (e.g. Choi and Ashdown, 2010; Shin and Chun, 2013; Choi and Hong, 2015; Wang and Wang, 2015), motion capture (Park and Hodgins, 2006) and a peel-off grid attached to the limb (Luo et al., 2017) have been applied to investigate skin deformation during specific exercise tasks. Knowing the different skin deformation rates of various body parts allows the precise design of garments, e.g. by using fabrics with different stretch properties at different body parts (Shin and Chun, 2013). However, there are still gaps in research on how to effectively quantify variations in body dimensions caused by movement and apply these variations into garment pattern design.

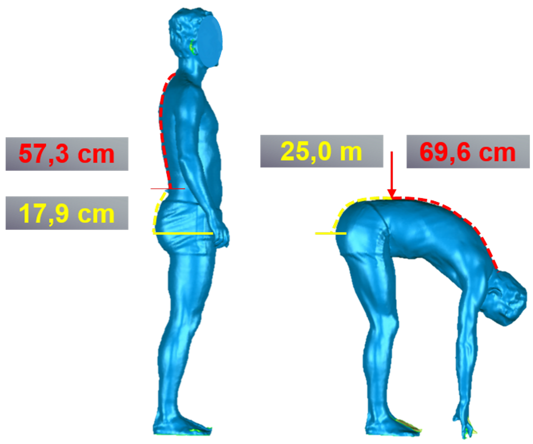


Figure 3.3: Variations in back (red) and seat (yellow) dimensions during bending movement captured with a 3D body scanner (Hohenstein Group, 2017)

For the design of SCGs anthropometric measurements are key, as the amount of pressure applied by SCGs depends on their size and fit, which are determined by the dimensions of the human body (Troynikov and Ashayeri, 2011). It is critical to define required anthropometric measurements purposefully, as measurements needed to classify body measurements and to develop clothing can differ considerably (Gill, 2018). Accuracy of landmark definition and allocation is crucial to reflect measurements required for pattern construction (Beazley, 1997; Bougourd et al., 2000; Simmons and Istook, 2003; Gill, 2009). Measurements required for the design of SCGs can vary substantially from measurements required for the design of clothing with positive ease and additional measurements are likely required to design precise pressure profiles.

3.3.2 3D Body Scanning

3D body scanners are optical 3D measuring systems that scan the human body from various angles capturing the surface geometry of the body and creating a digital copy of the body from which a large variety of anthropometric measurements can be extracted (Daanen and van de Water, 1998; Simmons and Istook, 2003). Whilst there are a variety of different 3D body scanning technologies, the basic principle is the same: a light source (e.g. white light, infrared, laser) projects light onto the body surface and a number of sensors record X, Y and Z coordinate data to remodel the body surface in a point cloud (Ashdown et al., 2008; Gill, 2015). 3D body scanners are connected to a computer and screen as 3D visualisation, measurement extraction and analysis is done in a special software programme that is generally part of the body scanner setup (Bougourd et al., 2000; Apeagyei, 2010; Daanen and Ter Haar, 2013). The 3D scanning software processes the raw point cloud to a triangulated mesh through the use of algorithms so that landmarks can be automatically detected and measurements can be extracted according to a customisable measurement extraction profile (Elbrecht and Palm, 2014).

Much more detailed analysis of anthropometric data can be performed using the scanning software than with traditional measurement methods (Simmons and Istook, 2003; Bye et al., 2006). Next to traditional linear measurements, 3D body scanners can extract a large number of custom measurements, slices of the body and determine volumes, which can be useful when analysing the distribution of body dimensions. The visual representation of the body also allows analysis of posture and body shapes (Gill, 2015). However, user friendliness of existing scan software for data analysis requires improvement for designers to be able to access the programmes (Brownbridge et al., 2013).

Scan data can be saved in file formats that are compatible with most 3D CAD programmes (e.g. .OBJ) (Elbrecht and Palm, 2014). This enables the use of 3D body scan avatars for virtual fit purposes or 3D printing. Examples of the most popular commercial 3D body scanners and their key characteristics are summarised in Table 3.2.

The anthropometric data extracted from 3D body scans has been found to have good validity and excellent reliability (Jaeschke et al., 2015). However, the accuracy of 3D body scanners depends on the technology (e.g. white light, infrared depth sensor, laser) and the number of sensors utilised (Elbrecht and Palm, 2014). The accuracy of body measurements extracted from 3D body scans also depends on the accurate identification of landmarks, which can be difficult as body landmarks are often only identifiable through palpation (Kouchi and Mochimaru, 2011). Currently the same landmarks are used for manual measurements and body scanning. It has been suggested that the definition of landmarks specific to body scanning could reduce errors in landmark location, as they would not be based on surface geometry, but surface geography (Gill, 2018).

As mentioned in the previous section, 3D body scanners can also be used to determine changes in body dimensions in different body postures. However, 3D body scan systems are currently not able to identify body landmarks when bodies are not in the standard scanning position (Chi and Kennon, 2006). This means that measurements have to be extracted manually from the point cloud or landmarks have to be manually defined using special software, which is a very time-consuming process (Choi and Ashdown, 2010). This is often accommodated by having visible markers placed on the scanning subject’s body.

Compared to manual measurements, the 3D body scanning process is faster, non-contact and objective (Chi and Kennon, 2006; Apeagyei, 2010; Jaeschke et al., 2015). Potential measurement divergences caused by body movement and varying tightness of the measuring tape are eliminated in 3D body scanning (Choi and Ashdown, 2010). One of the key advantages of 3D body scanning is that the anthropometric data can be stored and a wealth of data and measurements can be derived from the scan at any point of time (Daanen and van de Water, 1998; Gill, 2015).

Table 3.2: Key characteristics of commercial 3D body scanners

	[TC]^2 Labs (Apex, NC, USA)		**Size Stream** (Cary, NC, USA)		**Vitronic** (Wiesbaden, Germany	**TELMAT Industrie** (Soultz, France)		**Cyberware** (Monterey, CA, USA)
Model	KX-16	TC2-19B	SS14	SS20	Vitus	SYMCAD II	SYMCAD III	WBX
Technology	Infrared depth sensors	Infrared depth sensors	Infrared depth sensors	Infrared depth sensors	Laser line	Structured white light	Infrared depth sensors	Laser line
Sensor heads	16	?	14	20	8	4	16 or 20	4
Point-point distance/ Point density	1mm	75 points/cm^2	1mm	1mm	27 points/cm^2	25 points/cm^2	25 points/cm^2	< 2mm
Scan duration	7s	1s	6-8s	< 4s	6-10s	≤ 1s	≤ 1.5s	17s
Colour scans	✓	✓	✓	✓	✓			✓
Automated measurements in dynamic postures						✓*	✓*	
Circumference measurement accuracy	3mm	< 1mm	< ±5mm	< ±5mm	< 1mm	±0.15%	±0.15%	NR
Avatar output format	OBJ	OBJ, WRL	OBJ	FBX	ASCII, OBJ, STL, DFX	ASCII, OBJ, PLY, STL, WRL	ASCII, OBJ, PLY, STL, WRL	ASCII, OBJ, PLY, STL, DXF
In accordance with ISO 20685			✓	✓	✓	**	**	

*in accordance with ISO 7250 using wireless markers; **in accordance with ISO 8559; NR = not reported

Problems with data occlusion, i.e. missing points in a body scan point cloud, can occur when the projected light is not visible on a body part or when the light cannot be detected by the sensors. Missing data often occurs in the areas where limbs join the torso (i.e. crotch and underarms) (Elbrecht and Palm, 2014). 3D CAD software can be used to manually move points of the body mesh or remove redundant points if the body surface of the visualisation looks uneven or incomplete (Ashdown et al., 2004). However, it is a very laborious and subjective process.

In order for 3D scanners to be fully utilised in the design of sportswear, automated measurements need to be tied to features and planes of the body, rather than those of the scanning environment to allow for automated anthropometric measurements of dynamic, sport-specific body postures to aid sportswear design (Gill, 2015).

3.3.3 Body Shapes

Human bodies not only vary in body measurements, but also in the proportions, composition and overall shape of the body. Standard sized clothing is designed for a specific body shape (typically hourglass) and divergence in body proportions and contours from the standard inevitably lead to garment fit problems (Beazley, 1997; Aldrich, 2004; Kwong, 2004). The ratio of bust-to-hip circumference measurements of 100 university students has been found to vary between 4 to 22cm, highlighting variations in body shapes across the population (Beazley, 1998).

Classifying different bodies according to their physique is known as somatotyping (Kerr et al., 1995). Whilst body type classification goes back to Hippocrates, the best-known contemporary approach of somatotyping was developed in the 1960s from the controversial work of Sheldon et al. (1940): the Heath-Carter method (Carter and Heath, 1990). It is still the most commonly used method of somatotyping in sport today (Kerr et al., 1995). The method expresses somatotypes in a three-digit number, indicating the degree of endomorphy (relative fatness), mesomorphy (relative musculoskeletal robustness) and ectomorphy (relative slenderness) of a body (Carter, 2002; Stewar et al., 2003; Carter et al., 2005). It is a common method to identify young talents for particular sports (Carter and Heath, 1990).

Douty (1968) was the first researcher to develop a somatotype method based on visual assessment of bodies via photographs using the Douty Body Build Scale and Douty Posture Scale. However, these somatotyping methods were not able to provide anthropometric data for clothing design.

The shape of the female body is more complex than the male body and has a higher fat percentage due to the female sex hormone oestrogen (Guyton and Hall, 2006). In the clothing environment, female body shapes have commonly been classified based on letters (e.g. H, O, A), geometric shapes (e.g. rectangle, oval) or fruit shapes (e.g. apple, pear) (Robinet, 2009). The main figure type terminology and characteristics are listed in Table 3.3.

Hourglass shapes are sometimes further divided into full hourglass, top hourglass or bottom hourglass (Vuruskan and Bulgun, 2011) when the upper and lower body are not equal, but slightly top-heavy or bottom-heavy, whilst still featuring a clearly defined waist.

Table 3.3: Most commonly used body shape terminology and characteristics (based on Simmons et al., 2004a; Rasband and Liechty, 2006)

Body shape terminology	Triangle Spoon Pear 'A'	Inverted triangle 'V'	Hourglass 'X'	Rectangle Ruler 'H'	Oval Apple Diamond 'O'
Characteristic	Upper body smaller than lower body.	Upper body larger than lower body.	Upper and lower body of equal proportions with small, defined waistline.	Upper and lower body of equal proportions with no defined waistline.	Narrow top and bottom with large midsection.
Illustration					

An individual's body shape is mainly determined by bone size and structure and weight distribution, but posture and age can influence body shapes (Rasband and Liechty, 2006). In addition, activity can influence the body's dimensions and shape. Different sporting disciplines result in the development of varying muscle groups. Depending on whether aerobic or anaerobic exercise is performed, these muscles develop either lean or bulky (refer Appendix A), resulting in body shape variations as shown in Figure 3.4.

It is important to consider that body shapes exist independent of an individual's body mass index (BMI) or garment size. Consequently, a variety of different body shapes exist within each size category. Because of the sometimes vast proportional variations across body shapes, it is difficult to design clothes that fit every body. Variations in body shapes present difficulties for the design of sized SCGs, as they are likely to create variations in garment fit that can translate into disparities in applied pressure.

Figure 3.4: Female elite athletes from a wide range of sports disciplines showcasing variations in body dimensions and shapes across different disciplines (Schatz and Ornstein, 2002)

3D body scanning can aid body shape classification. Connell (2006) developed the Body Shape Assessment Scale (BSAS©) to visually evaluate 3D body scans. The system is based on nine 5-point ordinal scales including the assessment of overall build, shape and posture, but also the shape of several body parts (hip, shoulder, torso, bust, buttocks and back), some of which were adapted from Douty (1968). The scales were later collapsed when integrated into a software tool. The evaluation of the tool highlighted problems with the classification of borderline shapes. This was to be expected since decisions are based on subjective visual assessments. To eliminate this problem and have objective cut-off points between each body shape category, several researchers have developed quantified approaches to classify female bodies into different body shape categories by calculating relations between body dimensions.

The first study to utilise 3D body scan data and most frequently cited system for mathematical body shape classification is the software-based Female Figure Identification Technique (FFIT) for Apparel (Simmons, 2002; Simmons et al., 2004a, 2004b). The system classifies bodies into shape categories based on ratios of circumference measurements extracted from 3D body scans and has been successfully validated (Devarajan and Istook, 2004; Lee et al., 2007). Lee and colleagues (2007) utilised the FFIT system to compare US and Korean body shapes using sizeUSA and sizeKorea data. It is not clear if the system would be suitable for other target markets.

Other systems using mathematical relationships of body dimensions have been developed (Rasband and Liechty, 2006; Gribbin, 2014; Makhanya et al., 2014), but it is difficult to make conclusive remarks about their suitability, as there are no publications verifying the proposed methods on a large-enough scale. Robinet's (2009) methodology for body shape classification was based on hierarchical clustering and is the only approach that is based on a large anthropometric data set. Because the system is based on data from a French sizing survey, it would likely only be valid for the French market. Appendix E presents a summary of the calculating formulae of the FFIT system and other developed systems.

Vuruskan and Bulgun (2011) found that numerical body shape classifications using width measurements had better accordance with visual body shape classifications conducted by four referees than numerical classification based on circumference measurements. The researchers argued that circumference measurements do not provide any indication about the weight distribution around the circumference. However, width measurements of a body are harder to measure. Unfortunately, the developed calculations were only based on a small sample. In order to address the problem of body mass distribution, which is hard to assess from circumference or width measurements, Mastamet-Mason (2008) combined a quantified with a visual approach. The approach involved the visual analysis of the body's silhouette and profile on a photograph to assess the body contour and particularly back curvature and buttocks and bust protrusion. The study and findings are limited to a particular Kenyan female population.

It is unknown whether any of the described methods have any practical application today. The problem with all approaches is that body shapes and dimensions vary across different cultures and sportspeople (Makhanya et al., 2014). Therefore, body shape parameters used for the US population are not necessarily applicable in Asian or European countries. Different parameters and formulae, thus, would have to be defined for each target group, however the anthropometric measurements used for this would have to be extracted from a population sufficient in size. It appears that a combination of both a quantification of anthropometric data and visual assessment of a body's 3D shape would result in the most suitable body shape classification for clothing development since the weight distribution across the body girth is critical to design garments with appropriate fit. 3D body scanning can assist the process, as body scan data can easily be viewed from any angle in 3D CAD programmes.

3.3.4 Garment Fit

Garment fit is the relation of a garment to the dimensions and proportions of the wearer's body (LaBat, 2006). It is, thus, directly related to the anatomy of the human body (Cain, 1950). The optimum relationship between a garment and body needs to be determined for each garment under considerations of garment and body dimensions, function, comfort, style and fabric properties (Gill and Prendergast, 2015; Watkins and Dunne, 2015). As SCGs have a negative ease, fit requirements diverge substantially from the traditionally defined fit principles of ease, line, grain, balance and set (Erwin et al., 1979). However, no fit principles for SCGs exist.

Fit in performance sportswear is even more critical than in fashion as inappropriate fit can inhibit the garment’s function (Luo et al., 2014). For SCGs, inappropriate fit can lead to insufficient pressure delivery and air gaps between the body and garments can affect thermal comfort and moisture management properties of SCGs (Luo et al., 2014). The fabric of SCGs needs to move with the wearer’s body and not bunch up (Textiles Intelligence Limited, 2014a). Garment fit is difficult to achieve for every wearer in ready-to-wear clothing due to the discussed intra-individual variations of body dimensions and proportions (Brown and Rice, 2014). There is an assumption that adequate fit is easier achieved with knitted garments than woven garments, due to the multidirectional extensibility of knitted structures, which easier conform to the 3D shape of the human body (Brackenbury, 1992; Krzywinski et al., 2001; Power, 2004; Power and Otieno, 2008). However, there are unusual difficulties in the development of knitted garments, as garment patterns need be adjusted based on the stress-strain behaviour of the fabrics used in the garment (Chen, 2007). It is, therefore, necessary to analyse fabric extensibility to achieve adequate garment fit (Troynikov, 2008; Mullet, 2015). With SCGs this is an especially complex task, as they are often designed to wrap muscle groups and apply varying levels of pressure to different areas of the body.

To evaluate the fit of a garment, the relationship between the garment and the wearer’s body is assessed against predetermined requirements. Most existing research focuses on the fit of woven garments. There appears to be a lack of research on the fit of cut-and-sew knit garments in general and particularly knitted sportswear.

Fit testing in the clothing industry is generally done by using a fit model with body dimensions that fit into the middle of the size range, representing the target customer’s body dimensions (Watkins and Dunne, 2015). Fit can be assessed by objectively rating the relationship between the garments to the body or by having the fit model or expert judge(s) rate the fit on a scale (Watkins and Dunne, 2015). Range of movement assessment is also critical for sportswear since it is designed to be worn during specific athletic movements (Boorady, 2011). A fully objective assessment of fit is never possible (Gill, 2018). As each method has its limitations, it can be advantageous to use a combination of fit assessment methods (Watkins and Dunne, 2015). Subjective fit assessments by individuals of the same body size and shape wearing the same garment can vary substantially, likely because the way individuals perceive garments depends on their own personal fit preferences, which has been shown to be affected by body cathexis (positive or negative feelings towards one's own body) (Alexander et al., 2005). Likewise, poor fit has been shown to affect body image perceptions (LaBat and DeLong, 1990). Some of the main reasons for fit problems have been summarised by Kwong (2004) as:

- Lack of standardisation,
- Problems with sizing and grading,
- Shortcomings in pattern making,
- Manufacture-driven conflicts,
- Consumer and industry perceptions of the body.

A number of researchers (Ashdown et al., 2004; Bye and McKinney, 2010; Song and Ashdown, 2010; Lu et al., 2014) have assessed the use of 3D body scanning for objective fit assessment. Whilst Ashdown and colleagues (2004) conducted an inter-assessor analysis, Bye and McKinney (2010) and Song and Ashdown (2010) compared 3D clothed scans to a fit assessment with live models wearing the same garments. Lu et al. (2014) took nude and clothed 3D body scans of a mannequin and superimposed them, then took cross-sections at various points. Most of the researchers see potential for the use of 3D body scans for fit assessments even though not all of the results were successful. The fact that body scans can be rotated, enlarged and saved for future reference and that databases of different bodies within one size category can be created are added benefits (Ashdown et al., 2004). The existing fit assessments were all done for garments with positive ease. The usefulness of 3D body scanning for fit assessments of SCGs has not yet been explored, but is expected to be limited as SCGs generally sit flat against the body. It could, however, be interesting to compare body scans of subjects in nude state and whilst wearing SCGs to identify if body dimensions and contours are altered by SCGs.

There are no known studies assessing SCG fit. Existing research on the functionality of SCGs does not report fit levels. As SCGs have a negative ease and are highly elastic, conforming easily to various body shapes, visual fit criteria would likely be limited to assessing that the garments fit like a second skin, do not create fabric folds and have an adequate length. Whilst SCGs compress the underlying body, they should not constrict the body at the garment hems and waistband, as this would lead to discomfort for the wearer. In addition, wearers' fit evaluations are critical for SCGs, as poor subjective fit can negatively affect athletes' comfort levels on a physiological and psychological level. There is also a link between clothing fit and body image (LaBat and DeLong, 1990; Grogan et al., 2013) that could affect athletes, but has currently been unexplored in the sporting environment (Gill, 2015).

Garment fit is one of the most critical elements in the design of SCGs, as it affects functional, expressive and aesthetic user needs (Bye and Hakala, 2005).

3.3.5 Pattern Design

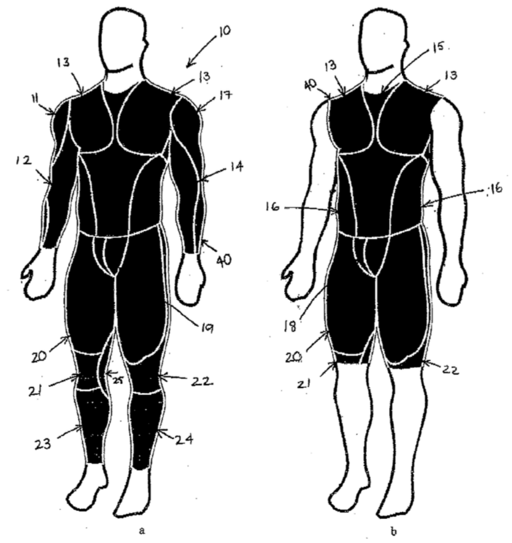
Garments are made by joining 2D fabric panels to create a 3D shape. The total number of fabric panels builds the garment pattern. Patterns are conventionally developed by defining the intended 3D garment shape in a 2D geometric coordinate system. This process of flat pattern cutting is generally based on adjusting a basic block pattern under considerations of human body dimensions and proportions and intended fit of the garment (Gill and Chadwick, 2009; Gill, 2011, 2018). It has been highlighted that there is a need to move away from the use of proportions towards the application of actual body measurements in pattern drafting (Gill, 2018). Patterns can also be designed in 3D by modelling fabric on a dress stand, where the pattern design is translated into 2D as subsequent stage (McCann, 2009b).

Patterns are generally developed based on static body dimensions, however, as mentioned in previous sections, for improved comfort and functionality in sportswear it is necessary to consider the postures and movements typical for the intended use situation (McCann, 2005; K. Liu et al., 2017). There is little guidance on how to design patterns for optimal functionality of performance garments.

Designers usually develop garments based on experimentation, trial and error, and experience or adaption of existing garments (McCann, 2005).

Traditional pattern making processes for woven fabrics are well documented (e.g. Shoben and Ward, 1998; Aldrich, 2004, 2015; Aldrich and Aldrich, 2013; Armstrong, 2013), however, manipulation of the basic block patterns for functional clothing and pattern making practices for knitwear, especially highly elastic knitwear, lack documentation (McCann, 2009b; Brownbridge and Power, 2010). Designing garment patterns for high-elastic knits that fit a 3D body varies substantially from pattern design for woven garments. There is practically no publication on how to apply anthropometric data to design patterns for SCGs.

In functional clothing design, it has been recommended to design patterns on the round rather than having traditional front and back panels, although little practical guidance exists (Gupta, 2011). Cutting lines should work in harmony with the body (McCann, 2009b). Lines of non-extension (refer Appendix A) should be considered when designing pattern panel shapes (Kim et al., 2012). For SCGs, pattern panel shapes often follow the shapes of major muscle groups to apply targeted compression (Perrey, 2008). It can, therefore, be useful to combine flat pattern cutting methods with working on a 3D form during the design development phase. However, when using a dress stand for pattern design, it is essential that it is representative of the intended target population (Di Marco et al., 2010; Armstrong, 2013). An exemplary SCG pattern design based on muscle group zoning is presented in Figure 3.5. Young (2009) filed a patent for the design of the whole-body CG with 19 pattern panels based on the surface anatomy of muscle groups. According to the author, the advantage of dividing the pattern into a large number of panels is the reduction of a ‘push-pull effect’ of the garment during movement. Watkins (2011) highlighted the importance of understanding the elastic properties of fabrics when designing patterns (refer section 3.4.1.1).



a) b)

Figure 3.5: SCG pattern panelling based on muscle groups for a) a whole body compression garment and b) a short no-sleeve compression garment (Young, 2009:1)

3.3.6 Sizing and Grading

Sizing systems are used for ready-to-wear clothing to categorise the population into different size designations, which should offer appropriate fit to each individual in one size of the size range (Watkins and Dunne, 2015). In reality, sized garments only offer perfect fit to a small number of people. Brands aim to offer adequate fit for as many people as possible, whilst trying to keep the number of sizes as low as possible, to avoid complexity in sizing selection and to reduce cost (Watkins and Dunne, 2015).

The process of developing sizing systems involves the analysis of body dimensions and shapes of the desired population and the correlation of key body dimensions (Pheasant, 1990). Due to the large amount of anthropometric data required, 3D body scanners are generally applied in size studies. Sizing systems are based on key measurements that determine each individual's size category (Bubonia, 2014). The key measurements for women's clothing are normally bust, waist and hip circumference measurements, as these are believed to be critical for the fit of garments (Apeagyei, 2010). However, people within the same size category may experience a different fit with the same garment, as most sizing systems only consider one body shape (Bougourd, 2007; Brown and Rice, 2014).

The nomenclature for the different size categories can either be numerical or alphanumerical (e.g. S, M, L). Numerical sizing offers more categories with category names varying across different countries. Alphanumeric sizing represents a collapsed numerical sizing system, which can have as little as three categories, but is frequently based on a 5-size-range (XS to XL). Close-fitting garments require a wider size range than loose-fitting garments in order to provide satisfactory fit (Mullet, 2015).

Every brand tends to apply their own sizing system, which is based on the body dimensions of their target customers despite international and national standards for sizing being in existence (De Raeve et al., 2011; Bubonia, 2014). This results in vast variations in sizing systems and size codes used leading to consumers being confused and dissatisfied, as they have to purchase different size categories across different brands (Otieno, 2008; Shoben, 2008; Mullet, 2015). There has been a trend towards vanity sizing, the concept of assigning smaller size codes to size categories to appeal to customers (Mullet, 2015). As mentioned in the previous sections, the relationship between clothing and the female body is complex making it difficult to create size charts. There are currently no publications on sizing systems for SCGs.

SCGs require optimal fit and contact with the skin to provide functionality. Most SCG brands utilise alphanumerical sizing systems that are based on body mass and height for lower body CGs and chest/bust circumference for compression tops. As a consequence, individuals within one size category are likely to vary in limb circumferences and body morphology. This can result in variations in pressure delivery, as has been shown in a recent study by Hill and colleagues (2015) who identified variations of up to 15mmHg at the calf within one size category of male participants. There are currently no studies analysing compression behaviour across the range of sizes.

The sizing system applied for lower body SCGs was likely derived from hosiery sizing systems, which conventionally use the relationship between height and body mass or hip girth and height to define size designations (British Standards Institution, 2017a). For medical compression stockings, the defining measurement for size designation is usually minimum ankle girth (Troynikov and Ashayeri, 2011).

Generally, patterns are developed in a size that is in the middle of the size range and patterns are then graded up and down to have garment patterns for each size in the size range. For this purpose, cardinal points on the master pattern are increased or decreased to accommodate the smaller or larger body dimensions incorporated within each size category, whilst maintaining the style and design of the garment (Mullet, 2015). This can be done using clothing-specific 2D CAD programmes. The grade quantity for each grade point needs to be given in X and Y values and is recorded in grade rules (Shoben and Taylor, 2004). Grading is done due to cost-constraints in clothing production, as only one pattern needs to be developed and fitted (Mullet, 2015).

The total grade, i.e. total change in body girth, is distributed across the body and added to the cardinal points at the perimeter of the different pattern panels. Differences in grade distribution can result in varying garment fit (Mullet, 2015). Traditionally, grading was based on horizontal and vertical measurements of the body in upright position (Lindqvist, 2015). In recent years, these methods have been increasingly criticised for not taking into account body shapes and variations in dimensional changes of the front and back of the body (Cooklin, 1990; Shoben and Taylor, 2004; De Raeve et al., 2011; Lindqvist, 2015). More complex grading systems are especially needed for close-fitting garments (Shoben and Taylor, 2004), however, such grading techniques are complicated and time-consuming. Hence, simplified grading systems are mainly used in the clothing industry. It has been reported that grading systems applied in industry are generally not based on anthropometric data, but on methods communicated through practitioners' experience (Schofield and LaBat, 2005).

When grading stretch garments, such as SCGs, it is essential to consider the fabric stretch and recovery properties since patterns are designed to be smaller than the body dimensions for each size category (Shoben, 2008; Mullet, 2015). The smaller width of the pattern is generally compensated by extra length, which converts in width when the garment is stretched (Shoben, 2008). Grading of stretch garments is usually done by using only a percentage of the change in body dimensions in X and Y direction, the conversion factor, as some of the dimensional change is compensated by the fabric stretch (Mullet, 2015). There is currently no published research on pattern grading of SCGs and how this could affect the level of pressure applied by SCGs.

Medical compression garments (MCGs) for the treatment of burn scars are usually made to measure. It is widely acknowledged that custom-made garments offer a more effective solution over ready-made-garments due to superior comfort and fit, resulting in more adequate pressure application (Macintyre and Baird, 2006; Macintyre, 2007) and athletic performance (Chowdhury et al., 2011), however it is currently not a viable solution for commercial SCG development.

It is possible that the most suitable sizing approach for SCGs differs from conventional sizing methodologies since the key aim of sizing of SCGs is to apply a uniform amount of pressure to the wearer’s body across the range of sizes, which is dependent on limb circumferences. A sport-specific sizing approach might be necessary for more elite ranges for certain sports in order to provide adequate fit to varying athletic body dimensions and shapes. There is no information about how compression brands currently fit and size SCGs. However, Adidas states on its website that “compression fit is one size down from regular sizing and stretches to give a supportive, next-to-skin feel” (Adidas, 2017). This statement suggests that the brand does not have a specific sizing methodology for SCGs, but only adjusts the nomenclature of its sizes. In general, brands consider their sizing systems to be confidential (Otieno, 2000). With each brand having developed its own sizing system, sizing is a competitive domain for clothing brands (Brownbridge and Power, 2010).

3.4 Textiles for Sports Compression Garments

Textile materials are the fundamental elements forming garments (Subic et al., 2016). Fabrics for sportswear should support comfort, freedom of movement and the thermoregulatory processes of the human body to provide the wearer with optimal conditions for maximum sports performance (Özdil and Anand, 2014). They should further be durable with easy-care properties (Voyce et al., 2005). Textiles used for SCGs are generally knitted fabrics.

Fabric selection is a key element of the product development of sportswear. Commonly specific fabric structures are used for different parts of the body, a concept called body mapping (Senner et al., 2009). The required fabric properties can differ depending on the sporting activity and environment (Özdil and Anand, 2014). In addition to the demands on general sportswear, SCGs have the particular requirement of applying pressure to the wearer's body.

3.4.1 Fabric Properties for SCGs

Fabrics used in SCGs need to support the skin's natural physiology in terms of thermal regulation, movement, fit and sensitivity (McCann, 2005). Some of the basic properties of fabrics include their weight, thickness and density as well as properties such as tensile strength, bending and formability, all of which can affect garment fit, quality and performance (Hunter and Fan, 2004). Fabrics used for SCGs should have good tactile comfort and biocompatibility as they are worn next-to-skin. They should also have good dimensional stability and controlled elasticity, stiffness and hysteresis for optimal pressure application (R. Liu et al., 2017). These properties are influenced by the fibre composition, fibre cross-section and orientation, yarn count and fabric construction of a textile structure (Troynikov and Watson, 2015).

Objective fabric testing methods exist to identify basic fabric properties. The first system developed was the Kawabata Evaluation System for Fabrics (KES-F) in the 1970s assessing the utility performance, comfort performance and manufacturing performance of fabrics (Kawabata and Niwa, 1998; Hunter and Fan, 2004). KES-F is a sophisticated system resulting in precise measurements of tensile and shear properties, bending, fabric thickness, weight and friction, however, it requires a skilled operator (Hunter and Fan, 2004; Power, 2013). A more straightforward system was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Wool Technology (Australia) in the 1980s, named Fabric Assurance by Simple Testing (FAST). The system measures fabric thickness, bending length, extensibility and dimensional stability with the intention of creating a 'fingerprint' of woollen suiting fabrics in order to foresee potential production issues (De Boos and Tester, 1994; Minazio, 1995). Today, both systems are used widely in research and testing laboratories, but not in industry as the systems are considered to be too time-consuming and specialised (Power, 2013).

3.4.1.1 Elastic Properties

Fabrics used in SCGs are very elastic. Even though they rarely stretch more than 70% during wear, the high elastane content of the fabrics generally allows them to extend more than 200% without rupture (Wang et al., 2011). As SCGs are designed to be smaller than the wearer's body, they stretch multidimensionally when donned and with body movement when worn (Wang and Zhang, 2013). As a consequence, the fabrics are subjected to various constant and changing levels of stress and strain during wear (MacRae et al., 2016). These internal stresses, including tensile, shearing and bending, act on the human body as pressure. Thus, applied pressure is affected by physical-mechanical properties of fabrics (Wang and Zhang, 2013).

One of the most critical properties of fabrics used in SCGs is their capacity to extend and recover to their original size (Wang et al., 2011). Extension and recovery properties influence the level of pressure applied by SCGs when new and over multiple wear occasions (MacRae et al., 2011). It is essential that SCGs recover fully (or at least within 3% of the original length) to maintain the level of applied pressure. There are currently no studies investigating the extension and recovery behaviour of commercial SCGs after repeated wear and laundering over a product's life.

Fabric relaxation occurs when fabrics are subjected to a constant level of strain, leading to gradual stress reduction (Morton and Hearle, 2008). When fabric repeatedly stretches and recovers, fabrics are reported to increase in length until reaching a stable point (Morton and Hearle, 2008). These behaviours are present when wearing SCGs with constant stress and strain as the SCG extends to fit the body and variable stress and strain occurring during movement of the body (MacRae et al., 2016). It is currently difficult to measure a fabric's dynamic extension and recovery properties. Instron® testing systems (Instron®, High Wycombe, UK) can be used to indirectly measure dynamic fabric extension and recovery, however, this method is only suitable for low-power stretch fabrics and does not capture the real fabric behaviour on the body, which is multi-directional (Hu and Lu, 2015). There are problems with slippage when testing elastic fabrics with Instron® testers, that is why Kielty et al. (2002) recommend using a burst tester where the fabric is clamped all around. There is a need for new methods that enable the assessment of high-power fabrics for the specific end-use of elastomeric garments (Hu and Lu, 2015).

Fabrics are very complex and anisotropic in nature (Gorjanc and Bukosek, 2008). The extension behaviour of fabrics differs from homogenous materials, as characteristics of fibres (e.g. friction), yarns (e.g. yarn thickness and rigidity), fabric construction (e.g. courses/wales per cm, stitch length) and fabric finishes can all influence the extension and recovery properties of fabrics (Nikolic and Mihailovic, 1996; Karimi et al., 2009).

When strain is applied to a fabric, it extends. Under low levels of fabric stretch fabrics can return instantaneously to the original shape upon release. This region of extension is the elastic region of a fabric. When stretched further past the yield point to the viscoelastic region, fabric stretch is no longer linear to the applied stress and takes time to recovery to its original shape (up to 24 hours). When the fabric is further stretched, plastic deformation occurs and the fabric does not return to its original shape (Nikolic and Mihailovic, 1996; Gorjanc and Bukosek, 2008). When fabrics are stretched within the elastic region, energy is lost during the recover process (R. Liu et al., 2017).

Ng (1995) and Berns and colleagues (2013) have highlighted the importance of fabric selection in providing uniform pressure application at varying degrees of fabric stretch caused by diverse limb circumference measurements of individual wearers. The researchers suggested the use of fabrics that result in a relatively constant fabric modulus under varying fabric elongation levels, such as the exemplary stress-strain properties shown in Figure 3.6. It is apparent from the stress-strain curve that changes to the fabric elongation within a range of 20 to 50% do not result in large variations of stress (Berns et al., 2013). This could reduce the effects that fabric stretch variations have on fabric tension and consequently applied pressure. Berns and colleagues (2013) suggested the use of fabrics with 22 to 30% elastic fibres of 40 to 80 denier. The researchers recommend that the modulus of elasticity of each fabric used in a SCG should be uniform in course and wale direction. It should further be consistent for fabric stretch of 20 to 80%.

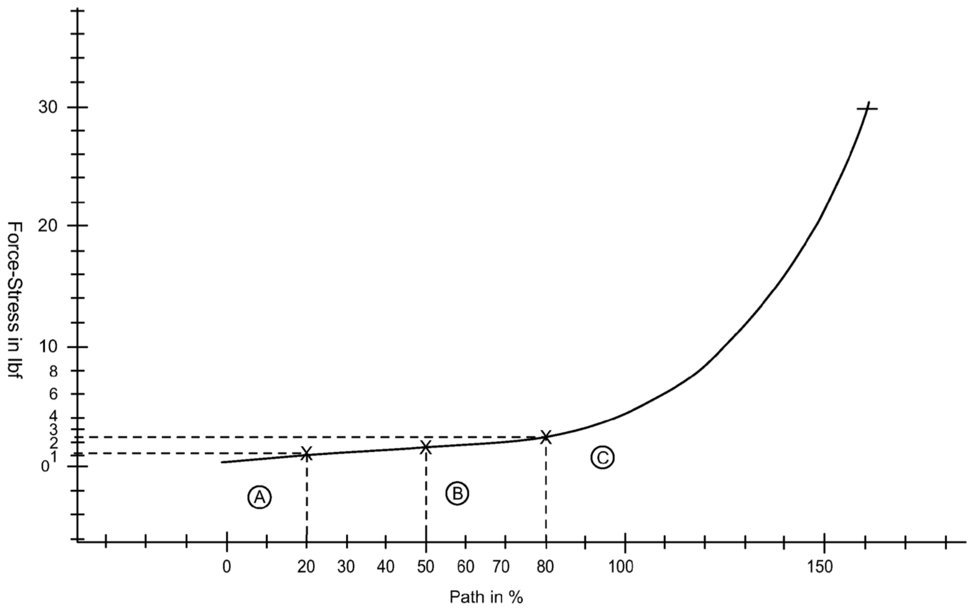


Figure 3.6: Stress-strain curve of exemplary modulus of elasticity of a stretch fabric used in compression sportswear (Berns et al., 2013:2)

3.4.1.2 Thermal and Moisture Regulation

Clothing is the closest environment of the human body creating a microclimate (Watkins, 1995). Garments worn next-to-skin, need to act like a second skin and support the body in managing its heat balance and thermal comfort. Heat balance exists when the body's heat production equals heat loss (McCullough and Kenney, 2003; Watkins and Dunne, 2015). Fabric properties, such as fibre and yarn types, fabric construction and finishes can affect the efficiency of thermal and moisture regulation of the body (Pascoe et al., 1994; Gavin, 2003).

In intensive training, an athlete's clothing moisture transport ranges from 1.5 to 2.5 litres per hour (Future Materials, 2006). Sweat interacts with clothing in both liquid and vapour form (MacRae et al., 2016). Sportswear fabrics are generally designed to wick liquid away from the body to the garment surface, where it can evaporate, or to transport water vapour of evaporated sweat away from the skin, which is facilitated by a stretched fabric (Liu et al., 2014). The latter creates more efficient heat loss from the body than evaporation from a fabric (Nagata, 1978). Most fabrics used for sportswear have quick dry properties to mitigate post-exercise chill through heat loss after exercise caused by residual moisture in the fabric (Bartels, 2005; Özdil and Anand, 2014; MacRae et al., 2016). This is especially critical for women, as they tend to get colder than men due to larger body surface area to mass ratio caused by a lower lean mass compared to men (Watkins, 1995; Foss et al., 1998; Bye and Hakala, 2005). Successful moisture management is further critical for fabrics used in SCGs, as moisture presence in the fabric increases friction and produces an unpleasant, clinging feeling on the skin (Troynikov et al., 2011; Ibrahim and Mahmoud, 2015). It could also affect pressure delivery (Macintyre et al., 2016).

The interactions of the body-clothing-environment are complex as they are also affected by the external environment (e.g. air temperature and movement, humidity) as well as activity levels (Liu and Little, 2009; Özdil and Anand, 2014). Fabrics insulate skin and can hinder the evaporation of sweat on the skin surface (Gavin, 2003). This can lead to increased skin temperature and inhibited heat transfer between the core and the environment, risking impaired sports performance (Nybo, 2010; Sawka et al., 2012; Phillips, 2015). Hence, it is essential that fabrics used in SCGs are breathable and allow wicking of sweat to the surface of the garment, especially in hot environments. Fabrics used in SCGs can often be comparatively thick to apply sufficient pressure, which can negatively affect thermal properties (Manshahia and Das, 2014b). However, research has not confirmed reduced performance when wearing SCGs during exercise, even though SCGs have been reported to increase skin temperature (Duffield and Portus, 2007; Houghton et al., 2009; Goh et al., 2011; MacRae et al., 2012; Venckunas et al., 2014; Priego Quesada, Lucas-Cuevas, Gil-Calvo, et al., 2015).

Garment design can optimise thermal regulation and through this improve sports performance by facilitating wicking and water vapour permeability (Özdil and Anand, 2014). One proven way to enhance thermal comfort of sportswear is to strategically place ventilation panels (e.g. mesh fabric) across the body to facilitate heat and moisture release and air circulation (Ho et al., 2008; Sun et al., 2015).

3.4.1.3 Comfort

Comfort is the state in which the human being is “psychologically, physiologically and physically in harmony with the surrounding environment” (Abreu et al., 2011:50). Thermal and moisture regulation, discussed in the previous section, are important aspects of comfort. Clothing comfort is extremely complex as it is influenced by interactions of physical and psychological aspects of the human body, garment and the environment (Emirhanova and Kavusturan, 2008). Wear comfort of SCGs can be divided into the following categories: thermophysiological comfort, tactile comfort, ergonomic comfort and psychological comfort. Further, fit can be classed as an element of comfort, which has been identified as the most important aspect of clothing comfort for wearers (Ashdown, 2011).

Whilst some aspects of comfort can be measured objectively, the overall sensation of comfort is a subjective perception of the wearer, hence the wearer should be at the core of comfort investigations (Liu and Little, 2009; Senner et al., 2009). This is especially true for sportswear, where discomfort can disrupt athletes' focus potentially leading to underperformance or even injury.

Subjective perceptions are formed by mechanical, thermal, electrical and chemical stimuli registered via sensory organs, sending neurophysiological impulses to the brain, where they are processed based on individual genetic disposition and experiences (Kilinc-Balci, 2011). As a consequence, subjective sensations and judgements of comfort vary widely across individuals and are likely to vary across recreational and professional athletes, as well as males and females (Gill and Prendergast, 2015).

Psychological aspects of comfort and attitudes and beliefs towards fabrics or garments can outweigh physiological factors for wearers (Kilinc-Balci, 2011). Hence, wearers' perceptions of clothing are critical. For SCGs, this could mean that perceived positive effects of SCGs result in positive psychological wear comfort, which could potentially outweigh comfort issues, such as a negative next-to-skin feel or fit perception (MacRae et al., 2016).

Liu and Little (2009) developed a model to assess user comfort of SCGs with the aim to optimise comfort and performance, called the 5P Model. The 5Ps stand for different comfort aspects: Physical, psychological, physiological, psychophysical and psychophysiological. Physical and physiological properties can be measured objectively, whilst psychological properties are measured subjectively, with the remaining two properties being measured both objectively and subjectively. The combination of objective and subjective assessments reduces the influence of the psychological status of the wearer at the time of judgement, yet considers important subjective sensations. The interactions of the 5Ps in context of SCG user comfort are presented in Figure 3.7.

In order to achieve the best possible level of comfort for a garment, the wear environment, garment design and style as well as the wearers' body movement and perceptions need to be considered. Whilst it is impossible to fulfil all comfort attributes, garments should be designed in a way that achieves an optimal combined comfort level of all properties (Kamalha et al., 2013).

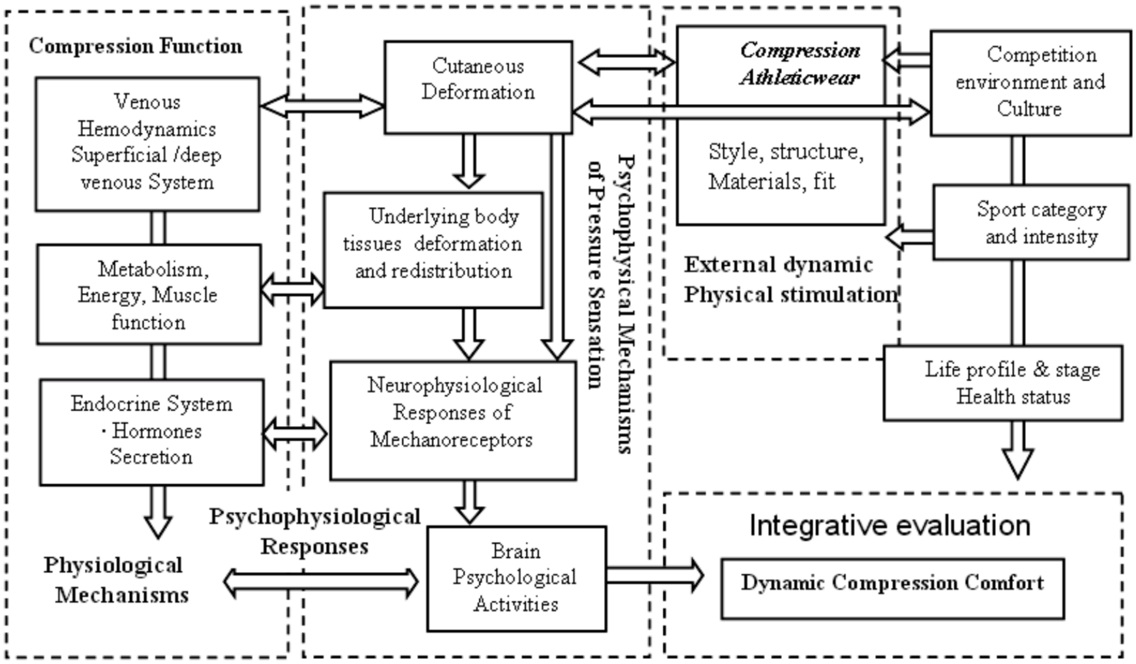


Figure 3.7: Interrelations of different 5P comfort properties of SCGs as defined by Liu and Little (2009:47)

Comfort for SCGs is critical as they are worn as a second skin and need to cover large parts of the body in order to apply pressure. Athletes only tolerate the use of SCGs if comfort is provided (MacRae et al., 2016). This means that fabric needs to provide thermo-physiological comfort and feel comfortable next-to-skin with no irritations (tactile comfort), as the skin is the largest organ of the body and most prone to injury during exercise (Manshahia and Das, 2014b). Troynikov and colleagues (2011) reported improved tactile comfort of fabrics for SCGs when stretched due to the widening of the loops in the knit structure, which reduces contact points and friction. Whilst SCGs need to be tight to apply pressure to the body, they should allow freedom of movement through optimal stretch and recovery properties (Emirhanova and Kavusturan, 2008; Fan and Hunter, 2009; Ibrahim and Mahmoud, 2015). Only few studies evaluating the functionality of SCGs consider psychological garment comfort (refer section 2.6.2).

An important aspect for SCGs is clothing pressure (Li et al., 2014). It has been reported to be one of the main factors influencing wear comfort (Kilinc-Balci, 2011; H. Liu et al., 2013; Bragança et al., 2015; Liu and Chen, 2015). Chan and Fan (2002) compared subjective tightness sensation of women's shape wear with in vivo pressure measurements (PM). The researchers found a moderate linear correlation with the rating of tightness on a scale of 1-7 and pressure levels and provided recommendations for optimal pressure levels. However, the sample size was fairly small and other aspects of comfort were not considered. You et al. (2002) highlighted the importance of fabric extensibility on clothing pressure as well as garment fit, underlining the importance of the interaction of fabric properties and garment design on wear comfort.

3.4.2 Fibres for Sports Compression Garments

The required fabric properties for SCGs described in the previous section can be positively influenced by the use of appropriate fibres. Stretch and especially the ability to recover, i.e. elasticity, is generally provided by elastomeric fibres. Elastomers are natural (e.g. rubber) or synthetic polymers (e.g. elastane) with a glass transition temperature below room temperature, meaning the material is flexible at room temperature (Wang et al., 2008). Elastomeric fibres can be stretched repeatedly to double their length, whilst immediately recovering to close to the original length (Kadolph, 2014). Elastane is widely used in sportswear, foundation garments and hosiery. Whilst elastane exhibits excellent elongation and elastic recovery properties and good resilience and dimensional stability, it has poor abrasion resistance and can be uncomfortable at direct skin contact (Kadolph, 2014). As a consequence, elastane filaments are usually covered by or blended with other fibres. In the case of SCGs, these fibres are generally polyester or polyamide (nylon 6 and nylon 6.6).

Polyester and nylon are widely used in sportswear due to their easy care properties and low cost (Özdil and Anand, 2014). Compared to natural fibres, such as cotton, they have better moisture management properties, which can result in improved physiological responses and performance during exercise (Hassan et al., 2012). Compared to polyester, nylon absorbs more moisture, has superior moisture wicking properties, but dries slower (Özdil and Anand, 2014). Nylon has a higher abrasion resistance and flexibility than polyester, however, polyester is more resilient and has a lower strength loss in wet state. Nylon has a substantial strength loss of approximately 10% when wet (Cohen et al., 2012). One of the key benefits of nylon is its excellent elastic recovery compared to polyester and other fibres, hence it is frequently used in hosiery and sportswear (Cohen et al., 2012; Kadolph, 2014).

Synthetic fibres can be modified to improve wear comfort or wicking properties through modification of the fibre cross-section or fibre treatments (Kadolph, 2014). Examples include polyester filaments with hexagonal cross-sections featuring grooves on the filament surface that support wicking and faster drying (e.g. Coolmax by DuPont) (Fangueiro et al., 2010) or improved hand feel of polyamide through air texturising (Özdil and Anand, 2014).

The fibre blend of SCGs is generally 8-25% elastane with the remainder being either polyester or polyamide (Kadolph, 2014; Textiles Intelligence Limited, 2014a). For comparison, the percentage of elastane in conventional stretch garments with ‘comfort stretch’ (e.g. socks or underwear) is 5-8% (Kadolph, 2014; Textiles Intelligence Limited, 2014a). The high elastane content of SCGs provides controlled stretch and recovery properties, resulting in SCGs that allow freedom of movement, but have a strong holding power to retain their shape (Shishoo, 2015). The polyester/elastane or polyamide/elastane yarns used for SCGs are predominantly very fine (Textiles Intelligence Limited, 2014a).

Fibre content and especially the percentage of elastane is also likely to influence levels of compression, however there are currently no known studies that isolate fibre content from other fabric properties in order to identify its effect on compression.

3.4.3 Fabric Constructions for Sports Compression Garments

Fabrics used in SCGs are predominantly constructed by warp knitting. Warp knits are generally more compact than weft knits and have less inherent stretch. They extend more in crosswise direction than length direction (Kadolph, 2014; Watkins and Dunne, 2015). This makes them more suitable for SCGs as the level of stretch and recovery can be controlled through the addition of elastane (Skins, 2016). Figure 3.8 shows the different loop structures and characteristics of weft and warp knits.

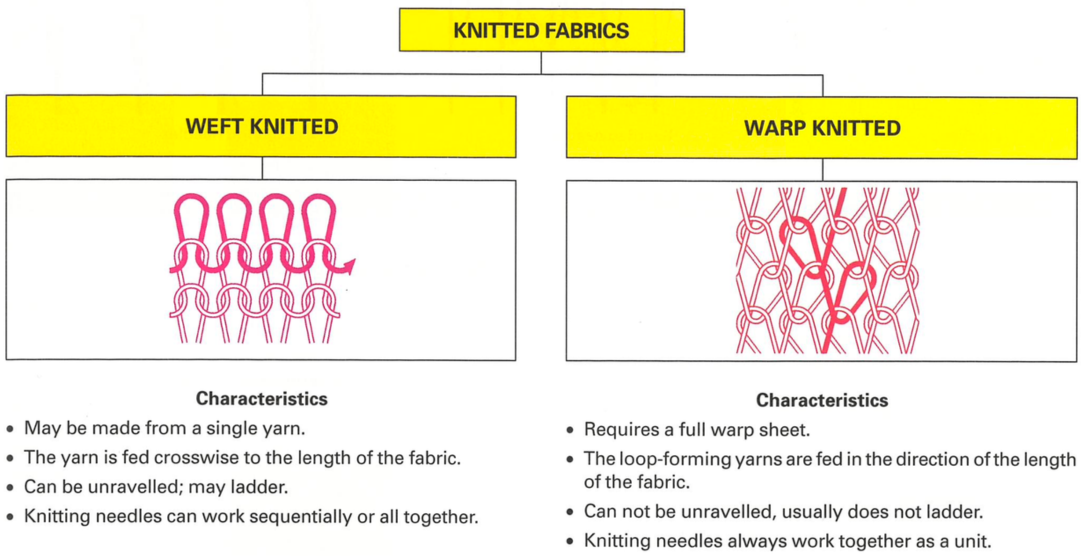


Figure 3.8: Loop structures and different characteristics of weft knits and warp knits (Eberle et al., 2004:83)

Warp knits are produced by a vertical loop structure by numerous needles creating loops with separate yarns simultaneously. The loops are connecting diagonally, resulting in one course. Warp knits can only be produced by flat knitting machines. Most warp knits are either produced on tricot or raschel machines. Tricot warp knits are most commonly used for SCGs with the face showing fine vertical lines and horizontal lines appearing on the back (Kadolph, 2014). The yarn count and density of the knit (i.e. number of courses and wales per unit area) affect the thickness and weight of the fabric (Subic et al., 2016), which in turn impacts the discussed fabric properties.

3.4.4 Fabric Finishes for Sports Compression Garments

To enhance the properties of fabrics used for SCGs, they are frequently treated with mechanical or chemical finishes. Mechanical finishes can increase comfort for instance through surface brushing. Chemical finishes are often incorporated to provide improved comfort and protection to the wearer. Examples of such finishes are:

- Antimicrobial/odour control treatments (e.g. Active>silver™ (Schoeller Textiles AG, Switzerland), HeiQ Fresh Tech (HeiQ Materials AG, Schlieren, Switzerland)),

- Antistatic treatments (e.g. ZEROSTAT® (Huntsman Corporation, The Woodlands, USA)),
- Temperature and moisture management treatments (e.g. Coldblack® (Schoeller Textiles AG), ADAPTIVE (HeiQ Materials AG))
- Stain release technology (e.g. PHOBOL® CP (Huntsman Corporation, USA)),
- UV protection (e.g. HeiQ Sun Block (HeiQ Materials AG)),
- Improved durability (e.g. HeiQ No Fuzz (HeiQ Materials AG)).

There have been increasing concerns about potential health and environmental risks of using chemical textile finishes. Most manufacturers of finishing technologies are addressing the problem by attempting to develop finishing technologies with lower environmental footprints and no health risks for wearers. It is important to consider potential risks for SCG wearers, since they are worn next-to-skin and are subjected to sweat. Hence, SCGs should not contain any problematic substances (e.g. organic phosphor compounds, organic halogen compounds) and colours need to withstand prolonged exposure to sweat and rubbing (ÖKO-TEST, 2015).

In order to further enhance the potential physiological benefits of wearing SCGs during exercise, SCGs made from fabrics enhanced with negatively charged ions have emerged (e.g. Canterbury of New Zealand, New Zealand). Studies have shown that the inhalation of negatively charged ions can improve the aerobic metabolism by reducing the heart rate and oxygen uptake (Inbar et al., 1982; Wiszniewski and Suchanowski, 2008; Wiszniewski et al., 2014), however other research has shown no positive effects of negatively charged ions (Ryushi et al., 1998). Burden and Glaister (2012) examined the effects of such compression tights by comparing sprint and endurance cycling performance of ten participants when wearing ionised compression tights, nonionised compression tights or control tights. The researchers' results showed no effects on sprint or endurance cycling performance by either ionic and nonionic compression tights compared to the control condition. However, it needs to be considered that the control condition involved a small level of compression and that the applied pressure was measured on a mannequin, not in vivo for each participant. This means that pressure levels across individuals could have varied significantly depending on the participants' body dimensions, potentially affecting study outcomes.

3.4.5 Fabric Properties and Compression

Fibre content, yarn count, fabric construction (e.g. tightness of knit structure) and resultant fabric weight are all likely to influence the level of pressure applied by SCGs. This means that the pressures applied by the same SCGs made from different fabrics are likely to vary (Macintyre, 2007). The complexity lies in identifying how these different mechanical fabric properties affect pressure levels. Several researchers (e.g. Wang et al., 2011; Chen et al., 2013; Bera et al., 2014; Liu et al., 2014; Maqsood et al., 2017) have measured effects of different fabric properties on compression pressures, however most of these have been conducted on MCGs and fabrics used for MCGs differ widely from fabrics used for SGCs (e.g. fibre content, fabric structure, area density). Furthermore, it is difficult to isolate fabric properties from one another and from other factors affecting compression, so each experimental set up has likely influenced pressure levels (e.g. PM device used, body form used etc.) making it difficult to make conclusive remarks.

It has been reported that bursting strength, extension, thickness and weight are important fabric properties for the design of SCGs (Wang et al., 2011), however, their direct relationship to applied pressure levels is not clear. Liu and colleagues (2007a) tested fabrics used in different medical compression stockings (MCS) using the KES-F and assessed the statistical differences between tensile, shearing and bending properties for MCS applying different pressure levels at the ankle. They found significant differences in tensile, shearing, and bending properties between the fabrics applying different levels of pressure and concluded that higher tensile strain and energy at a given force and lower values in bending rigidity resulted in lower applied pressure values. However, unfortunately the researchers did not measure the applied pressure, but used the pressure values reported by the MCS manufacturers.

There seems to be a consensus that fabrics with higher resistance to deformation apply higher levels of pressure. In medical compression, the static stiffness index (SSI) is a commonly applied concept reflecting the pressure difference between active standing and lying (Partsch, 2005) and relates to the stiffness of the material as it counters muscle expansion during contraction (R. Liu et al., 2017). From a textile technology point of view, a fabric's resistance to extension is the elastic modulus (Saville, 1999). Fabrics with high elastic moduli require more load to achieve a set extension than fabrics with lower elastic moduli (Saville, 1999; Chen et al., 2013). As a consequence, fabrics with higher elastic moduli apply higher levels of pressure as was shown in a study by Chen and colleagues (2013). The researchers also assessed the effect of fabric relaxation, i.e. stabilisation under certain stress load, on clothing pressure using compression sleeves on cylinders. The main fabric relaxation occurred within the first 30 minutes and resulted in some loss of applied pressure. Pressure levels only decreased slowly from 30 to 600 minutes and remained stable after 600 minutes. Overall, the pressure loss was only a small proportion of the total pressure. The level of fabric relaxation is affected by the tightness of the knit structure, filament cross-sections and fineness of the elastane filaments since they influence friction between yarns and fibres. Lower friction levels allow yarn and fibre slippage, which increases fabric deformation and results in a faster pressure drop, whilst higher levels of friction are thought to maintain internal stresses for longer with stress relaxation occurring at a slower rate (Manshahia and Das, 2014a).

Effects of variations in fibre content on pressure delivery are yet to be understood. Fibre content variations of nylon, cotton and elastane for MCGs did not result in significant pressure differences (Bera et al., 2014), however different compositions of sports compression sleeves led to variations in applied pressure (Troynikov et al., 2013). Although, the researchers could not identify a relationship between the material composition percentage and applied pressure levels. Moreover, they produced compression sleeves from two different fabrics to create variations in fibre compositions, which is seen as problematic, as the two different fabrics also had different fabric properties, which would have affected applied pressure levels. The variations in fibre properties in the study by Bera and colleagues (2014) were mainly in the percentage of cotton and nylon. The elastane content did not vary significantly. It is believed that substantial variations in elastane content would lead to variations in pressure application, as it affects the fabric's elasticity.

Maqsood and colleagues (2017) compared the compression properties of knitted and bi-stretch woven fabrics used for MCGs over time. Whilst the study focus was on the comparison of the properties of knitted and bi-stretch woven structures, the most important aspect of the study for this research lies in the measurement of the effects of laundering on pressure application; an aspect that has been neglected by existing research. There was a substantial loss of pressure after 15 washes compared to pre-wash measurements. It has to be considered that the fabrics used in the study were made from cotton/elastane core spun yarns, so no inferences can be drawn for pressure behaviour of SCGs. However, the research opens up the question of pressure behaviour over a product's life. More research on the effects of wear and care on compression properties is needed.

One of the most critical issues in the design of SCGs is the realisation of controlled compression across the body following a pre-determined pressure profile. To achieve this, it is important to understand the elasticity, elastic modulus and hysteresis properties of the fabrics used for SCGs (R. Liu et al., 2017). Most studies examining the effects of SCGs on exercise performance and recovery ignore fabric properties. The properties of the textile materials used to construct SCGs have substantial effects on pressure application. Whilst the link between the various fabric properties and applied pressures is currently not fully understood, it is critical to report basic fabric properties to allow for comparisons of different studies assessing the functionality of SCGs. According to MacRae (2011), these basic properties should include the fibre content, fabric structure, thickness and area density.

3.5 Construction of Sports Compression Garments

3.5.1 Cut-and-Sew Garments

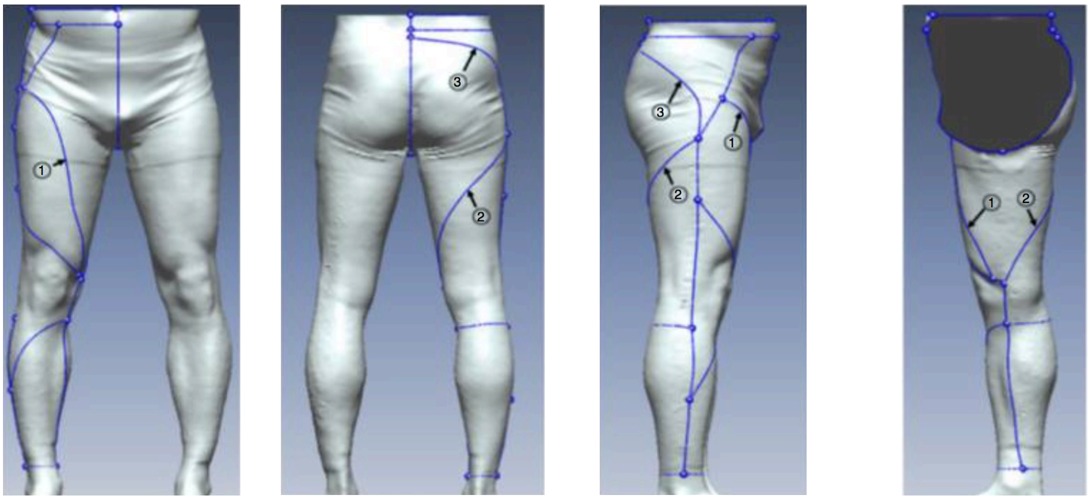
The phrase 'cut-and-sew' is used in the clothing industry for the traditional method of creating garments by cutting panels from fabric lengths and joining them together by sewing to create a 3D garment. Most garments and knitted sportswear are created using this method (Troynikov and Watson, 2015). For cut-and-sew garments, garment panels are cut from pre-knitted flat fabrics, which can result in substantial cut-loss (up to 30%). The separate fabric manufacturing and garment creation processes make it a high labour- and time-consuming process, which is why it is generally outsourced to Asian or Eastern European countries (Peterson and Ekwall, 2007).

3.5.1.1 Construction of Cut-and-Sew Garments

It has already been discussed in section 3.3.5 that garment patterns for SCGs need to be adjusted based on the stretch properties of the fabric used (Choi and Ashdown, 2010). In sportswear, garment patterns should be designed in a way that ensures optimal fit of the garment on the wearer's body and allows for the required freedom of movement for the specific sporting activity. Because SCGs are skin-tight and should mimic the skin's extension, it is useful to apply pattern panels of different strain, which are joined by seams (Choi and Hong, 2015). This is also the case when different parts of the body require different levels of pressure application. The garment pattern determines the location of the seams, i.e. the location where different fabric panels are joined together. The consideration of seam positioning on the wearer's body is critical for sportswear and particularly SCGs, as if not carefully placed, seams could adversely affect freedom of movement and comfort.

The concept of lines of non-extension (refer Appendix A) has been applied by researchers to identify optimal seam positioning for cycling (Choi and Hong, 2015) and outdoor pants (see Figure 3.9) (Heeran Lee et al., 2017) using 3D body scanning technology to ensure optimal garment function.

In order to get the most ergonomic pattern design and seam placement, skin stretch directions and lines of non-extension, body movement patterns for the specific use situation and body part sensitivities need to be considered.



a) b) c) d)

Figure 3.9: Proposed seam placement for men's outdoor pants based on analysis of skin extensions during movements: a) front; b) back; c) outer leg; d) inside leg (Heeran Lee et al., 2017:159)

3.5.1.2 Seam Properties

For cut-and-sew SCGs it is not only important to design patterns for optimal fit and compression and select the most suitable fabrics for the application, but also to select the most appropriate construction method as it can have a significant effect on the performance of the finished product (Shishoo, 2015). This involves the selection of the most suitable stitch type and thread. The correct choice of seam is critical because the performance of a seam in terms of strength, flexibility, elasticity, appearance, comfort and permeability affects garment quality and needs to act jointly with the garment (Jana, 2011; Beaudette and Park, 2017). A key consideration for SCGs is that seams need to support the garment's stretch and recovery behaviour. Seams need to have sufficient extension and strength to avoid thread breaks when the SCG is stretched during donning, doffing or wear. There are various international standards for stitches and seams. The relevant British Standard (1991a, 1991b) divides stitches into six categories:

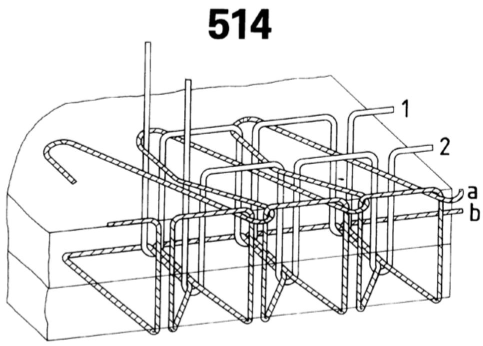
- Class 100 chain stitches,
- Class 200 hand stitches,
- Class 300 lockstitches,
- Class 400 multi-thread chain stitches,
- Class 500 overedge chain stitches, also overlock stitches,

- Class 600 covering chain stitches, also flatlock stitches.

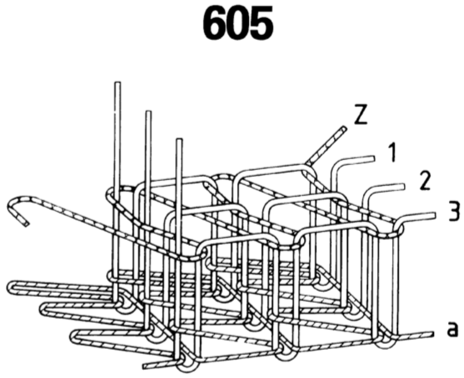
Overlock (e.g. ISO 514) and flatlock (e.g. ISO 607, ISO 605) stitches (refer Figure 3.10) have the most extensibility and are, therefore, frequently used for the construction of stretchy sportswear (Beaudette and Park, 2017). Overlock seams are strong and inexpensive, but they are superimposed seams creating bulk on the inside of the garment, which can be irritating to the wearer, especially in the armpit or crotch areas of close-fitting garments (Jana, 2011). Having flat seams is especially critical for SCGs due to the tightness of the garments and can reduce chafing and potential abrasive injuries (Bubonia, 2014). Hence, flatlock seams are widely used for SCGs (Textiles Intelligence Limited, 2014a). Due to the high thread consumption, flat lock seam and are more expensive than other stitch types (Beaudette and Park, 2017).

Flatlock seams are produced with a minimum of two plies of fabrics butted together at the raw edge (McLoughlin and Hayes, 2015). The ISO 605 and ISO 607 top and bottom cover stitches sit flat next to the skin making them comfortable, whilst being durable due to good tensile strength and elasticity (Beaudette and Park, 2017). For improved next-to-skin comfort and smoothness, bulk cover threads can be used as sewing threads (Hayes, 2018).

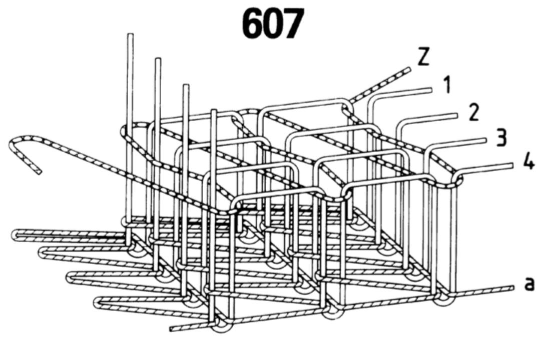
Stitch properties (e.g. stitch length, seam allowance, thread tension, thread properties) need to be adjusted for optimal seam extension (Hayes, 2018). These properties need to be compatible with the extension and strength properties of the materials to be sewn to ensure optimal pressure application (Ng, 1995).



a)



b)



c)

Figure 3.10: Most common stitches used to construct SCGs: a) ISO 514 four-thread overedge stitch; b) ISO 605 five-thread cover stitch; c) ISO 607 six-thread cover stitch (British Standards Institution, 1991a:42, 46, 48)

Non-stitch construction methods for performance sportswear made from a high percentage of synthetic fibres are on the rise due to reduced bulk and weight and potentially cleaner appearances (McCann, 2009b; Jana, 2011; Beaudette and Park, 2017). These novel joining techniques include bonding using adhesive, thermoplastic films, pressure and hot air as well as ultrasonic or laser welding. However, these non-traditional joining techniques are not suitable for all applications, as there are currently still problems with seam elasticity and flexibility as well as joining of deep curves (Jana, 2011). As a consequence, most commercial SCGs are currently manufactured using conventional stitch methods, however some garments feature adhesive bonding at hems.

Beaudette and Park (2017) evaluated the thermal properties of overlock (class 500), flatlock (class 600) and adhesive seams using thermal mannequin Walter® (Hong Kong Polytech University, Hong Kong). They found a significant difference in thermal insulation across the three joining methods with the flatlock seam providing the highest level of thermal insulation. However, the seams' water vapour transport properties did not vary significantly. The high-density stitches of flatlock seams seem to trap still air leading to increased thermal insulation (Beaudette and Park, 2017). So it needs to be considered that flatlock seams offer extensibility, strength and tactile comfort, but may increase thermal insulation of the wearer's body. Like any design decision in functional clothing design, each method and material has positive and negative influences on the garment's performance, which need to be carefully outweighed. There are currently no known studies investigating seam properties of SCGs.

3.6 Designing SCG Pressure Profiles

When developing SCGs, it is crucial to design garments to given pressure specifications. It is essential to predict the pressure levels that the finished garment will apply to a body of known size within the design phase.

3.6.1 Technical Considerations

Understanding the pressure behaviour of the final garment when designing SCGs is a very complex task because of the many interrelating factors influencing pressure levels, discussed in the preceding sections. Compression exists at the interface of SCGs and the human body. The garment is constructed from fabric using construction methods and, thus, defined by fabric and construction properties as well as garment dimensions. The human body is defined by its dimensions and surface texture, and variations to these caused by body movement during sporting activities. All these aspects influence the level of pressure applied to the wearer's body as summarised in Figure 3.11.

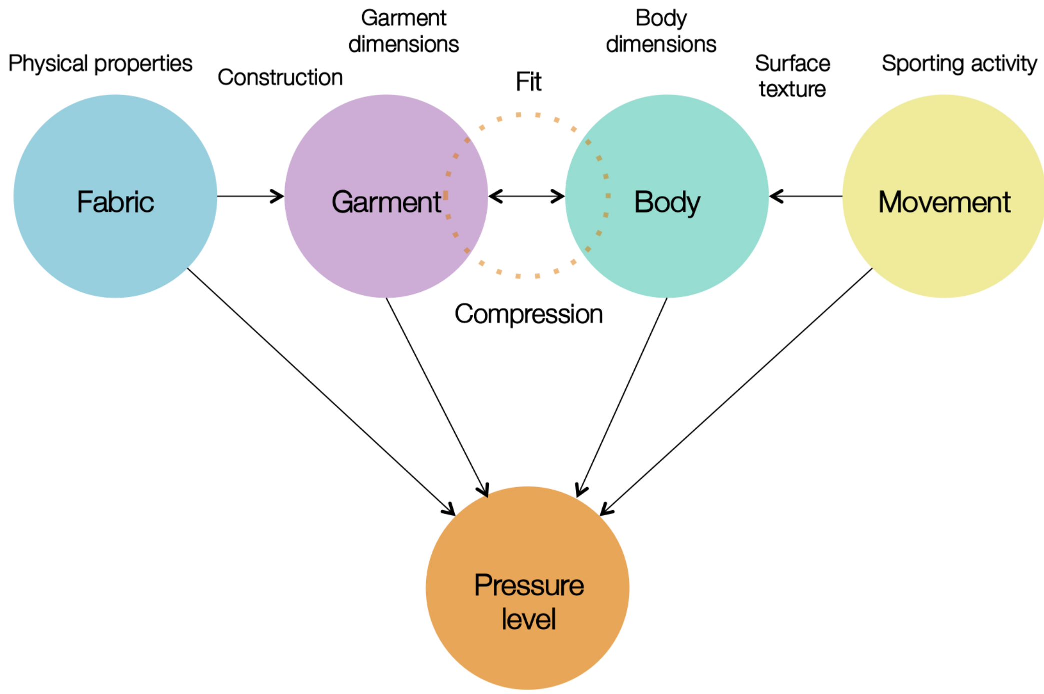


Figure 3.11: A simplified view of the complex interactions of SCGs and the human body affecting pressure application

Many SCGs feature a combination of graduated and targeted pressure designs. However, there are no studies that provide evidence on which pressure profiles offer the most benefits to sports performance or post-exercise recovery (Brophy-Williams et al., 2015). Regardless of which pressure profile (uniform, degressive, progressive or zoned) results in optimal performance for the wearer's body, designers need to be able to predict the defined pressure profile in the design phase in order to make design decisions and design patterns that result in prototypes featuring the desired pressure levels. The ultimate aim of designing pressure profiles for ready-to-wear SCGs must be for the SCGs to apply a uniform pressure level to the diverse range of wearers within and across the range of sizes.

3.6.2 Calculations Based on Laplace's Law

With not much literature on the design of pressure profiles for SCGs, it is essential to look at the design of MCGs. MCGs are generally custom-made in hospitals using the patient's body dimensions and a reduction factor (Macintyre, 2007). The reduction factor is the value by which the body measurements are reduced to obtain garment measurements with negative ease (Aiman et al., 2016). The principle is based on Laplace's Law, hence the tension of the applied fabric and the radius of curvature of the body part requiring compression are needed for the reduction factor calculation (refer Eq. 5) (Aiman et al., 2016):

$$Re = \frac{1}{1 + \frac{E}{P \times r}} \qquad \text{(Eq. 5)}$$

where Re = reduction factor, E = fabric tension in N/M, P = pressure to be exerted in Pascal, r = radius of curvature in metre.

However, hospital staff producing these garments generally simply use a reduction factor of 10, 15 or 20% without consideration of fabric properties (Macintyre, 2007).

When considering Laplace's Law, it is evident that it is not difficult to design graduated pressure patterns in compression tights, as the radius of a leg naturally increases from ankle to thigh. Therefore, compression tights using a fabric with a constant amount of tension, apply more pressure at the ankle than at the thigh, as the garment is generally designed to match the contours of the body (Perrey, 2008).

In order to produce the same level of pressure on different sized limbs, a larger reduction factor is required for larger circumferences because a larger radius needs higher fabric tension to produce the same amount of pressure as a smaller radius (Aiman et al., 2016). This is important to consider in sizing for SCGs.

Small changes in reduction factors on small cylinders resulted in large differences in pressure levels, whereas changes in reduction factors on larger circumferences resulted in comparatively smaller pressure variations, as was shown by Ng (1995).

Other researchers (Maklewska et al., 2006; Leung et al., 2010) have also successfully designed basic MCGs based on the principle of Laplace's Law. In order to design SCGs to predetermined levels of pressure, Maklewska and colleagues (2006) recommended obtaining force-extension curves of the fabric at various extension levels, whilst Leung and colleagues (2010) highlighted the use of different fabric biases to yield varying elastic moduli.

Macintyre (2014) developed three different tools based on Laplace's Law for the design of MCGs. Unlike other experimental developments in pressure prediction, these tools were designed with the application environment in mind. Two of the tools were based on reduction factor methods to calculate pattern dimensions and expected applied pressure levels (Macintyre and Ferguson, 2013). The third tool was developed to help practitioners develop graduated CGs based on limb circumferences (Macintyre, 2014). The tools were based on specific fabrics that had been tested and equations for the design tools were developed based on the test results. Unfortunately, each new fabric used would require extensive testing and re-calculation. As the tool was based on Laplace's Law, pressure values represent the mean pressure values across a circumference. If the body part is non-cylindrical, pressures would be higher in areas with small radii and lower in areas with higher radii of curvature, i.e. in flatter body regions (Macintyre, 2014). The models were also only suitable for very basic compression sleeves, not whole-body SCGs with body-mapped design using a number of different fabrics.

Salleh and colleagues (2015) developed a model for the prediction of pressure levels exerted by customised MCGs using 3D body scanning. The model was based on five steps:

1) Measurement of body part in need of compression using a 3D body scanner,
2) Calculation of fabric modulus,
3) Calculation of reduction factor for body part circumference,
4) Calculation of radius of curvature for each data point in a given layer,
5) Obtaining pressure level.

The researchers found that their model worked on an incompressible body model, but resulted in overestimation of pressure values on human bodies. These findings highlight the importance of measuring pressures in vivo and the significant impact that body tissue composition and soft tissue deformation have on applied compression.

It can be assumed that the basic principles of Laplace's Law are used in the practical design of SCGs today, however, no evidence exists. The approaches used by SCG brands to design garments with distinct pressure levels are treated as proprietary information. The same seems to be the case in academic research. Anand and colleagues (2013) developed a pattern cutting chart for MCGs by modifying Laplace's Law to predict "actual sub-garment pressure more accurately over a very wide range of limb dimensions" (Anand et al., 2013:663). However, the researchers did not disclose the new formula due to Intellectual Property Rights protection.

The above-mentioned studies are all based on basic MCGs covering body parts to support the healing of burn scars. Fabric properties and patterns of these garments vary substantially from SCGs. The described models require substantial calculations and are not easily applied in a practical design environment.

The brand Under Armour (Baltimore, MD, USA) has filed a patent for the design of a whole-body one-piece SCG with uniform compression (Berns et al., 2013). Dimensions of the SCG to be designed are calculated based on body dimensions of the median measurements of the target population for each size category and target elongation of the garment (Eq. 6). The formula to calculate garment dimensions was defined as follows:

$$M = \frac{\frac{1}{2} \times B}{E + 1} \qquad \text{(Eq. 6)}$$

where M = garment flat measurement (i.e. width), B = body measurement and E = target elongation (i.e. the target percentage of fabric stretch expressed as a decimal).

Garment dimensions need to be calculated for multiple body locations; it was suggested to define locations approximately every 15cm along the leg for the lower body. Once the garment dimensions are calculated, pattern panels can be designed to match these dimensions. The target elongation, a medial amount of stretch within a range, is determined by the stress-strain curve of the fabric so that deviations within the stretch range do not result in large stress variations (refer section 3.4.1.1). When the target elongation is defined this way, the final SCG is claimed to apply a relatively constant amount of pressure to about 90% of wearers within the size category (Berns et al., 2013). However, Under Armour base their size chart for compression tights on a combination of height and weight of the wearer rather than circumference measurements, meaning that a large variation of limb circumferences may be present within one size category. Even if fabric tension was not affected too much by differences in fabric stretch, variations in limb circumferences would result in varying pressure levels according to Laplace's

Law. The design approach highlights the importance of fabric selection when designing SCG pressure profiles and when combined with a size chart that considers limb circumferences, has the potential to offer relatively uniform inter-individual pressure levels. The Under Armour patent is the only known design methodology for SCGs.

3.6.3 3D Modelling to Predict Pressures

3.6.3.1 Finite Element Modelling

There have been a number of researchers (e.g. Liu et al., 2006; Rong Liu et al., 2007; Dan et al., 2013, 2015; Li et al., 2014; Chassagne et al., 2018) modelling CGs or bandages using Finite Element (FE) models in an attempt to predict pressures applied by SCGs. FE models utilise numerical calculations to simulate objects and their material properties. Some researchers have chosen to simulate the human body as elastic elements (e.g. Dan et al., 2013, 2015), whilst others have simulated them as rigid objects (e.g. Kobayashi et al., 2016).

The clear advantage of FE modelling over simply numerical modelling lies in the possibility to model the exact limb geography. It has been shown that the use of circumferences only is not adequate in the design of effective MCGs, as variations in curvature are not taken into account (Kowalski et al., 2012). Especially concavities can change the expected pressure distribution on specific body areas (Gaied et al., 2006). It is difficult to measure body curvature manually, hence, 3D body scans are the best solution to realistically represent body parts for 3D modelling, as has been done by several researchers (e.g. Dan et al., 2013, 2015; Li et al., 2014). To simulate body composition, including skin, bones and soft tissues, some researchers have used magnetic resonance (e.g. Liu et al., 2006; Rong Liu et al., 2007) or computerised tomography (e.g. Dubuis et al., 2012) images to realistically reconstruct limbs. The latest research (Chassagne et al., 2018) modelling compression bandages on a scanned human leg is based on a non-numerical, model reduction approach. The researchers concluded that their model was superior to Laplace’s Law, as it considered variations in limb curvature and size.

Whilst FE modelling is the most accurate method of simulating fabric behaviour on a human body model, existing studies have only modelled basic compression sleeves on body parts, likely because of the vast computational requirements of FE modelling, making complete garment simulation impossible (Volino and Magnenat-Thalmann, 2005). It also needs to be considered that FE modelling is a time-intensive process requiring advanced technical knowledge beyond the spectrum of clothing designers or technologists. The application of FE modelling within the practical SCG design environment is, therefore, not feasible. CGs in sportswear are much more complicated and usually composed of various pattern panels with varying material properties, making it a complicating endeavour to realistically simulate garments and predict pressures.

3.6.3.2 Clothing-specific 3D Computer-Aided Design

Over the past decade, 3D simulation technologies enabling the virtual ‘sewing’ of 2D garment patterns around body avatars have been developed (Porterfield and Lamar, 2016). However, cloth simulation is far less matured than the simulation of solid objects in other industries due to the anisotropic character of fabrics, which needs to be simulated in combination with the forces exerted by the body wearing the garment (Volino et al., 2005).

Most 3D CAD software systems feature built-in heat maps that enable the subjective and objective evaluation of fit and garment design prior to producing physical samples (Sayem, 2017a, 2017b). These heat maps indicate tension, pressure, stretch or ease levels across the avatar’s body with red indicating the maximum value and blue representing the lowest value (Lim and Istook, 2011; Sayem, 2017a). If these pressure map tools realistically represented pressures applied by a garment to the underlying body, they would be a simple means to control pressure levels and distribution of the finished SCG throughout the design phase. It could also facilitate the production of custom SCGs for athletes.

Overview of Clothing-specific 3D Computer Aided Design

3D CAD software programmes specific to the needs of the clothing industry have been on the market since the early 2000s, though, adaptation by the fashion industry is reported to be poor in contrast to 2D CAD programmes, which are firmly established in pattern development, grading and cutting processes of clothing product development (Goldstein, 2009; Lee and Park, 2016; Sayem, 2017b). Whilst the exact adaptation rate of 3D CAD in clothing design is unclear, studies have shown hesitance by designers to fully rely on virtual fit to make design decisions (Porterfield and Lamar, 2016). In other industries, such as architecture or engineering industries (e.g. automotive industry), the use of 3D CAD is much more integral in the design and development process than in clothing design. Unlike the simulation of solid objects, 3D CAD for clothing design has the specific technological challenges of simulating realistic representations of the human body and soft cloth and its respective characteristics when worn on a human body (Goldstein, 2009). These challenges have slowed down initial adoption (Porterfield and Lamar, 2016).

3D CAD programmes are generally linked with 2D CAD software programmes (Porterfield and Lamar, 2016). 2D garment patterns can virtually be draped around human body avatars that are either integrated into the 3D CAD software or imported from a 3D body scan. Some programmes also allow the design of 3D patterns on the avatar by ‘drawing’ garment panels on the avatar, which can then be ‘peeled off’ the body and flattened to 2D patterns. Several studies (Kang and Kim, 2000; Yunchu and Weiyuan, 2007; Istook, 2008) have researched this feature, however, it is currently only suitable for knitted, tight-fitting garments and the process is not without difficulties (Gill, 2015; Mahnic Naglic et al., 2016).

Once 2D patterns are in the 3D system, certain properties need to be applied to each pattern panel in order to enable the simulation of the garment. These properties include fabric properties for the realistic draping behaviour of the fabric as well as details about the location of the pattern panel on the body and allocation of seams to enable virtual stitching of the garment. 3D CAD programmes generally have built-in fabric libraries with their appropriate mechanical properties. Whilst it is possible to manually adjust fabric properties, the values used by the 3D CAD programmes to calculate the drape algorithm are not directly related to fabric properties obtained through standard objective fabric testing methods, such as KES-F and FAST. Until recently some 3D CAD programmes (e.g. Browzwear and Optitex) incorporated fabric convertor tools to convert KES-F or FAST data into the relevant parameters of the CAD system. This function has recently been removed by Browzwear and Optitex and the software companies have introduced their own fabric testing kits, however, as has been highlighted by Power (2013), these systems lack standardisation and accreditation. Power (2013) compared extension and shear parameters obtained through FAST and Browzwear’s fabric testing kit.

The researcher found that there was a significant difference in the conversion of the objective fabric measurement data to the parameters required for simulation.

The simulation of garments on body avatars can be evaluated subjectively or objectively using heat maps expressing garment pressure, tension or distance to the body. For designers and manufacturers, the use of virtual fit can be useful in the evaluation of garment patterns and designs prior to making physical garments, reducing sample development time and cost (Goldstein, 2009; Hwan Sul, 2010; Park et al., 2011; Sayem et al., 2012; Lee and Park, 2016). 3D virtual simulation has not only the potential to increase efficiencies and communication in the technical design process, but also in the use of virtual try-on technology in online retail.

Several researchers have assessed the accuracy of virtual fit simulations, however due to the heterogeneity of studies in terms of garments and 3D CAD programmes used, it is impossible to draw conclusions from these studies. Porterfield and Lamar (2016) highlighted variations in methodologies in existing studies with some researchers assessing cross-sections of the virtual model (Apeagyei and Otieno, 2007; Lu et al., 2014), whilst others compared virtual garment fit to real garment fit on a mannequin (Wu et al., 2011) or human bodies (Lim, 2009; Kim and LaBat, 2013; Lee and Park, 2016; Lin and Wang, 2016). Lee and Park’s (2016) findings indicated that fewer fit issues were detected in the virtual garments compared to the real garments likely due to the simulation technology providing ideal drapes and a lack in detailed, realistic garment visualisation.

Whilst 3D CAD programmes are currently able to produce visualisations of garments that are close to the realistic shape, there are shortcomings in the realistic representation of technical aspects, such as fabric and seam properties (e.g. thread type and size, tension) (Lee and Park, 2016). These shortcomings can significantly affect fit analyses conducted using virtual fit.

Jevsnik and colleagues (2017) see great potential in virtual prototype technologies to advance the traditional clothing industry. However, in order to make 3D CAD an integral tool for day-to-day tasks in the clothing industry, it needs to offer improved user friendliness (Goldstein, 2009) and realistic representations of technical fabric and seam properties (Lee and Park, 2016). Table 3.4 provides an overview of the features of the most prominent commercial 3D CAD software tools.

Table 3.4: Overview of the key features of commercial clothing-specific 3D CAD programmes

		VStitcher (Browzwear, Singapore)	O/Dev 3D Product Creation Suite (EFI Optitex, Israel)	AccuMark® 3D (Gerber Technology, USA)	Modaris® 3D (Lectra, France)	Vidya (Human Solutions GmbH, Germany)	TUKA3D (Tukatech, USA)
Design features	Integrated 2D module (same window)		✓				
	Virtual fit (2D to 3D)	✓	✓	✓	✓	✓	✓
	3D to 2D pattern edit		✓	✓		✓	
	'Draw' on body 3D to 2D design		✓				
	Rendering for realistic display	✓	✓	✓	✓	✓	✓
Cloth simulation	Fabric library	✓	✓	✓	✓	✓	✓
	Objective fabric test input				✓	✓	
	Proprietary fabric testing kit	✓	✓				
Garment simulation	Technical seam parameters		✓				
Body simulation	Resizable parametric models	✓	✓	✓	✓	✓	✓
	Target group specific models					✓	
	Import of body scan avatars	✓	✓		✓	✓	✓
	Body measurements in 3D		✓	✓		✓	
Body-garment assessment	Heat maps	Tension Pressure	Distance Stretch Tension Normal collision pressure	Tension Pressure	Distance	Distance Stretch	Tension Pressure
	Dynamic postures	✓	✓	✓*	✓	✓	✓
	Animation in motion	✓	✓			✓	✓

*only for parametric models

Simulation of Fabrics and Garments

Cloth simulation is much more complex than the simulation of solid objects due to the anisotropic characteristics of fabrics. Since the 1980s, a variety of deformation models have been developed all differing in the way geometry, deformations and forces are translated into simulations (Miguel et al., 2012). New models generally aim to improve simulation accuracy and efficiency (Wu et al., 2011). Simulation models for deformable structures in mechanical engineering are based on mechanical models, however, they are not suitable for the simulation of cloth due to the highly versatile nature of fabrics (Volino et al., 2005). Mechanical fabric properties are non-linear and folds and wrinkles occur, which are difficult to predict. It is further not possible to standardise processes due to variations in assembly steps in different garment types (Liu et al., 2010).

There has been a division between the aims of different industries using simulated clothing. Whilst the animation field focuses on a realistic visual simulation of garments, for example for computer games, the garment industry requires simulation of fabrics and garments to be technically realistic to be able to use 3D simulations for technical garment evaluations (Power, 2013). Computer graphic developers do not always understand the technical behaviour of fabrics. Due to the described complexity, only limited fabric properties can be inputted into 3D CAD systems.

3D CAD models for virtual fit must not only realistically simulate the specific non-linear fabric properties, but also reproduce the effects of geometrical contacts of the fabric with the moving body and other clothing layers on fabric behaviour (called collision detection and response) (Volino and Magnenat-Thalmann, 2000; Volino et al., 2005; Mahnic Naglic et al., 2016). The accuracy of virtual fit depends largely on the computer-based fabric models used to simulate garments (Volino et al., 2005; Nilay et al., 2016; Jevsnik et al., 2017). Spring-mass-like particle systems are fast and versatile, but lack accuracy in the simulation of realistic behaviour of complex anisotropic fabrics (Volino and Magnenat-Thalmann, 2005).

Most 3D CAD programmes feature fabric libraries with pre-set properties for certain fabric types. As mentioned, the input of objective fabric properties is not or no longer possible in most 3D CAD programmes. For clothing-specific 3D CAD programmes to be efficient and virtually fit a garment onto an avatar in as little as a few seconds, their cloth simulation model is generally based on geometric approximations (particle grid systems) resulting in loss of accuracy (Power, 2013).

To create a model for fabric simulation, a relationship between the deformation and fabric properties obtained by objective fabric testing (e.g. KES-F, FAST) needs to be created to establish a link between real fabric behaviour and cloth simulation. However, limitations of the fabric tests are that they measure one or two components at a time (e.g. stretch, bending), isolating individual deformation modes. This uniform approach can cause errors in modelling (Miguel et al., 2012). Wu et al. (2011) used the FAST system to measure mechanical properties of 20 woven fabrics and simulated them in a skirt pattern. They concluded that it was not recommendable to fully rely on virtual fit, as simulation results varied significantly for some of the fabrics used. This highlights the necessity of accurate simulation of fabric properties, which if not provided, can lead to inaccurate fit judgements (Kim and LaBat, 2013).

Existing research has focused on defining new models for more realistic cloth simulation (e.g. Miguel et al., 2012, 2013), however, there is no research exploring the technically realistic simulation of seams.

Simulation of the Human Body

The accurate representation of the human body is critical for virtual fit and prototyping. A limitation of all 3D CAD programmes is that body avatars are solid objects in 3D CAD. As such, soft tissue and bony prominences in the body cannot be represented realistically. This could affect the way a garment fits the body and can affect pressures applied by the virtual garment onto the underlying body simulation.

3D CAD programmes generally have a selection of built-in body avatars of varying age and gender, here referred to as parametric models, which can be morphed to various sizes and body shapes. Some measurements can be amended by entering absolute values, others by sliders. However, many measurements are limited or linked to other measurements, so that a fully user-defined adjustment of parametric models is not possible. In addition, the distribution of mass within a circumference (e.g. more mass in front of body or back) can generally not be adjusted, making it difficult to recreate body shapes. Researchers (Stjepanovic et al., 2010; Mahnic Naglic et al., 2016) have compared the use of parametric models and body scan avatars for the design of customised functional garments (ski jumpsuit and dive suit, respectively) using 3D CAD. Whilst parametric models are easy to use and symmetrical in shape (Mahnic Naglic et al., 2016), a more accurate representation of a human body can be achieved through the import of 3D body scan avatars (Yu et al., 2012; Baytar and Ashdown, 2015). However, depending on the quality of the 3D body scan, this may require substantial cleaning and retopologising of the avatar. Stjepanovic and colleagues (2010) found significant differences between the parametric model and body scan avatar, which translated into variations in the developed ski jumpsuit created through a 3D-to-2D pattern design technique. The researchers recommended the use of body scan avatars for improved garment design. This study highlighted the importance of accurate body avatars for virtual fit and 3D design.

Virtual Fit for Pressure Prediction

Several researchers (e.g. Lim and Istook, 2011; Wu et al., 2011; Olaru et al., 2014, 2015; Porterfield, 2015) have utilised heat maps to evaluate garment fit. Fit assessments based solely on the visual assessment of the colour coding of the 3D CAD heat maps have been found to be not sufficient as a decision making tool in design and product development (Kim, 2009; Lim, 2009; Power et al., 2011; Kim and LaBat, 2013; Power, 2013). As per default setting, heat maps generally present the respective maximum value in red and the minimum value in blue for each garment independently of the absolute value. This makes it difficult to compare heat maps across garments.

Only assessing colour codes is subjective and significant variations in values could be overlooked as differences in colour nuances can be small (Power, 2013; Sayem, 2017a). Lim's (2009) study was particularly interesting, as it compared two different 3D CAD systems (Optitex and Vstitcher). The researcher found that the visual appearances of the simulations with identical fabric properties differed and that the use of fabric parameters and avatars affected simulations, highlighting limitations of 3D CAD programmes. Only few researchers (Allsop, 2012; Sayem, 2017b; Sayem and Bednall, 2017) have included the numerical values provided by heat maps in their analyses. Sayem (2017b) and Sayem and Bednall (2017) utilised tension, stretch and pressure maps to evaluate the drape of developed men and women’s sleeveless shirt patterns, respectively, with varying ease levels at the chest using converted FAST data for fabric parameters. Sayem and Bednall (2017) found significant correlations between changes in ease and tension as well as stretch levels and concluded that ease levels can be predicted using virtual fit. However, the researchers did not assess the accuracy of the visual simulation or numerical values provided by the three different heat maps.

One of the earliest studies to assess virtual fit as a tool for pressure prediction was conducted by Seo and colleagues (2007). The researchers developed a virtual fit programme based on a mass-spring model described by Volino and Magnenat-Thalmann (2000). They validated the ability of the programme to accurately measure the pressures applied by the simulated garment to cylinder objects by comparing virtual pressures to real-world measurements recorded using a pneumatic PM device. The researchers concluded that the cloth simulator was a valid tool to measure the pressure applied by close-fitting clothing to cylinders. However, the authors assumed linearity of mechanical fabric properties, whereas fabric properties are generally non-linear in reality. Allsop (2012) further explored the concept of virtual fit for pressure prediction by comparing the distribution of pressures applied by men’s compression tops to a mannequin with virtual pressures using a parametric model in Vstitcher. The researcher reported difficulties with simulating a garment with slightly higher levels of complexity and with pinpointing specific pressure values for comparison. Hence, she only compared pressure distribution rather than absolute values, and reported similarities at some parts of the upper body, but found discrepancies at others. Limitations to Allsop’s (2012) study include the use of a parametric model and the disregard of simulation settings. Whilst she used converted FAST data for fabric parameters, the researcher did not report stitch parameter settings similar to other studies using heat maps (Sayem, 2017b; Sayem and Bednall, 2017).

There is currently no published research comparing absolute values of in vivo and virtual pressures of commercial 3D CAD programmes. If the pressure map of a 3D CAD programme could be used to predict pressures applied by SCGs to underlying bodies, it would present a simple method to facilitate the design of SCGs to desired pressure specifications.

3.7 Current Trends in Sports Compression Garment Design

In recent years, the SCG offering has advanced with a wide variety of garment types and styles being available for male and female amateur and elite athletes. Most major sportswear brands have developed their own CG ranges with varying technology focus. There is a growing number of SCG specialists with many brands offering a unique twist on compression technology as they are trying to gain a bigger market share. These brands are the driving force of SCG innovation and many collaborate with research institutions in the attempt to further improve their technology and prove the efficacy of their products (Textiles Intelligence Limited, 2014a).

From a design perspective, most SCGs apply body-mapped zoning and contoured panels for improved functionality. This creates a sports aesthetic associated with innovation and high performance (Brownbridge, 2015). Following on from the trend for brightly coloured and printed sportswear, SCGs, initially mainly available in black, are now being offered in an array of colours and prints. This development goes in line with a shift from wearing SCGs as base layer to wearing it as primary outer layer (Palmieri, 2014). A growing number of brands are now also offering recovery-specific CGs. These garments are designed to be worn for an extended period of time post-exercise (e.g. over night).

In order to differentiate themselves from the competition, some brands integrate additional functions into their garments, such as kinesio-type taping (e.g. CW-X) and zoned impact protection (e.g. Nike Hyperstrong Compression Elite range). Kinesio taping uses elastic tape with 55-60% stretch, which is believed to stabilise muscles and joints and through this increase functional control, however solid evidence is lacking (Williams et al., 2012; Mills et al., 2015). Some brands have applied this principle to SCGs by adhering silicone tape to the inside of the garments. Under Armour have applied the concept of printed support elements on SCGs by printing PU coating to the outside of SCGs at targeted areas of the muscles in order to enhance compression at these locations (Under Armour, 2018). Examples of the aforementioned SCG trends can be found in Appendix F.

Due to the different foci of SCG brands, there are big differences in the various compression products on the market. Pressure levels and gradients, fabric and construction methods all differ from brand to brand making an overall judgement about the functionality of SCGs impossible (Senner et al., 2009). In order to gain market share over their competitors, brands promote the alleged benefits of their products and claim that they can provide athletes with a competitive edge by improving their performance, accelerating recovery and reducing the risk of injuries (refer Table 3.5). However, with convincing scientific proof lacking (refer section 2.6), there are claims that the advertisement slogans of SCG brands are exaggerated (Textiles Intelligence Limited, 2014a; ÖKO-TEST, 2015). ÖKO TEST (2015) asked twelve sports compression sock manufacturers (including Adidas and Skins) for scientific evidence of their advertised claims. Most brands highlighted beneficial results of individual studies, but excluded studies that showed the opposite effect. The studies often did not involve compression socks, but CGs, such as tights. It seems like most brands take the scientific evidence out of context and do not consider all relevant studies in order to promote their products, potentially misleading consumers.

Table 3.5: Examples of claims about the effects of wearing SCGs made by SCG brands

Brand	Claim
2XU (2015)	Greater oxygenation of blood for faster recovery Reduced fatigue through less muscle oscillation Reduced muscle soreness Reduced long-term overuse injuries Faster muscle warm up pre-exercise Greater power output Heightened proprioception – awareness of limb placement for agility
Adidas (2017)	Supports muscles and posture, boosting power output and energy efficiency
CW-X (2017)	Increased stability and balance Greater efficiency of movement Better shock resistance in joints Decreased muscle oscillation Increased circulation Faster recovery
Skins (2016)	Increased muscle oxygenation Stabilisation of active muscles Reduced blood lactate build up Enhanced performance Faster recovery

3.8 Chapter Conclusions

The design of SCGs is a complex endeavour. The ability to design SCGs with controlled pressure profiles seems to have been underestimated by researchers, whilst the effects of SCGs appear to be overemphasised by SCG brands selectively choosing research studies to ‘prove’ the benefits of their products. The following key considerations for the design of SCGs have emerged from the review of related literature:

- It is critical to understand users’ needs on a functional, expressive and aesthetic level.
- Fit and comfort have been identified as key considerations in the design of SCGs, as they affect pressure application and sports performance.
- Textile materials and structures directly affect the performance of SCGs. Fabrics used in SCGs need to have superb thermo-physiological properties, controlled elastic properties and optimal tactile comfort.
- It is critical to consider sport-specific anthropometric data due to variations in body dimensions and shapes across different sporting disciplines.
- The design of SCGs is higher in complexity in terms of fit and pattern design than conventional sportswear, as pressure levels are impacted by variations in fit. Sizing is complex and demands adaptations to a variety of morphologies, which so far has not been considered by SCG brands.
- It is essential to use flat seams in the construction of SCGs.
- Approaches to predict pressures using pressure maps in clothing-specific 3D CAD programmes show potential, however more research is required as quantified evaluations are lacking.

To create a better understanding of the relationship between the body and SCGs, there is a need for research investigating the design development of SCGs with particular focus on fit, sizing and fabric properties. Further, research studying SCG users and their needs and behaviours is required to be able to design SCGs that meet consumer needs.

4 RESEARCH METHODOLOGY

4.1 Chapter Introduction

This chapter specifies the research methodology designed to achieve the research aims of this study by gradually constructing the methodological framework and research strategy. It describes means of data collection and the adopted analytical approach together with potential limitations and ethical considerations of the chosen approaches.

4.2 Research Perspective

The research perspective is the starting point in the development of the research methodology, as it builds the theoretical foundation that underpins the whole study. The philosophy and concepts that guided the researcher's thinking are described below.

4.2.1 Philosophical Perspective

The way researchers see and interpret the world in which they interact creates the basic framework for every research methodology. Ontology, the nature of reality, and epistemology, the way knowledge is generated, are key aspects that define a research philosophy (Bryman, 2016). The researcher's perspective is that an external reality exists, which is, however, not independent. This ontological view goes in line with critical realism. Pragmatism and critical realism are similar in approach, but pragmatism is more interested in finding workable solutions to problems, whereas critical realism seeks significance in "higher-order, structural truths" (Proctor, 1998:368) to understand the reasons for existing phenomena (Easton, 2010). The fundamental idea of this study to develop new, applied knowledge was more at home in the pragmatist paradigm. The research philosophy of this study was, therefore, founded upon pragmatism.

In pragmatism the external world is presupposed to be real, yet transient (Dalsgaard, 2014). As such, the external world is never stable and assumptions of reality are only temporary constructs that result from experiences with reality at a given time (Johnson and Onwuegbuzie, 2004; Rylander, 2012; Dalsgaard, 2014).

This interaction between human beings and reality is a dynamic process of mutual adaptation, which is the premise for the emphasis of practice in the pragmatist paradigm (Rylander, 2012).

Pragmatism developed at the end of the 19th century in the USA with major contributions by Charles Sanders Peirce (1839-1914), William James (1842-1910) and later John Dewey (1859-1952) and George Herbert Mead (1863-1931) (Dalsgaard, 2014). While there are major divisions between the ideas of the different philosophers, an element that is often condemned by critics of pragmatism (Rylander, 2012), the common values are founded upon the view that practical consequences are a “vital component of both meaning and truth” (Hevner, 2007:91). This anti-dualist stance rejects the idea that emotion and reason or thinking and action are separated (Rylander, 2012). Consequently, the epistemological view of the pragmatist researcher sees theory only as acceptable knowledge when it is merged with practice. Theories are valued when they are embedded in practical experience and inform or improve the external world (Wang and Hannafin, 2005; Rylander, 2012; Dalsgaard, 2014). Pragmatist research, therefore, is experimental and emergent as it tests ideas against practical outcomes (Rylander, 2012).

Pragmatist researchers are open to different types of knowledge and understanding and through this also methods and approaches (Onwuegbuzie and Leech, 2005; Östmann, 2005). Nevertheless, Dewey was a strong supporter of scientific research and preferred research methods of the natural sciences (Östmann, 2005). Dewey’s view differed from the classic natural sciences, in the way that he thought that securing knowledge about things we already know was not sufficient, he aimed at creating new knowledge, which would have positive practical implications (Östmann, 2005). As a consequence, there is a strong focus on ‘real world’ problems in pragmatist research.

This study was based on the pragmatist views outlined. The study focused on a ‘real world’ problem as it explored design considerations that can improve design research and practice of sports compression garments (SCGs) rather than abstract theoretical concerns. As a consequence of this philosophical approach, conclusions drawn from this study are not absolute truths, but are current knowledge that was constructed under the specific research circumstances, which are seen as “provisional truths” (Johnson and Onwuegbuzie, 2004:18) that inform effective practice. Therefore, the design framework resulting from this study serves as a guide upon which more practical theory can build as future research develops.

4.2.2 Relevant Concepts

Next to the philosophical perspective of the researcher, there are other relevant concepts that informed the research approach and underpinned the research methodology.

4.2.2.1 Pasteur’s Quadrant

Pasteur’s Quadrant was first described by Stokes (1997) in an attempt to challenge the fundamental understanding of scientific research, which was based on the dichotomy of basic and applied research, and has since been described by many researchers from varying disciplines ranging from education (e.g. Berliner, 2004; Tierney and Holley, 2008; Mendoza, 2009) to instructional technology (e.g. Reeves, 2000) and medicine (e.g. Krajewski and Chandawarkar, 2008). Stokes (1997) argued that basic and applied research are not in opposition and proposed combining them to achieve high-value research of high rigour and relevance. He developed a matrix to categorise research based on whether researchers are concerned about the quest for fundamental understanding, the practical uses of the research or both. Stokes named the quadrants after scientists that represent examples of the type of research in each quadrant (see Figure 4.1). He contrasts Bohr’s knowledge-driven research on the structures of the atom (upper left quadrant) with the American inventor Edison’s application-driven invention of the phonograph (lower right quadrant). The upper right quadrant is reserved for research that combines these two forms of research, such as Pasteur’s work on microbial growth and pasteurisation, which was inspired by the quest for understanding within the context of solving practical problems. The lower left-hand quadrant is characterised by being neither inspired by the goal of understanding nor by use, therefore disqualifies as research approach.

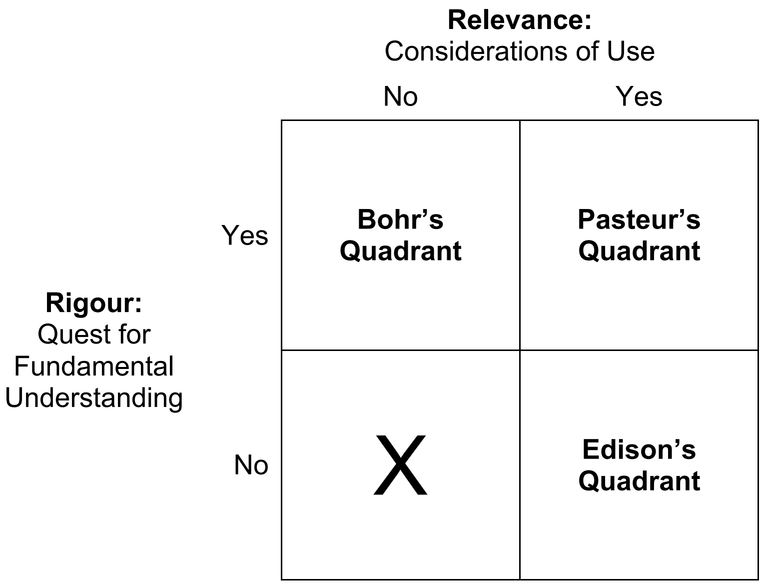


Figure 4.1: Three different approaches to research (adapted from Stokes, 1997)

Stokes (1997) proposed that research within Pasteur's quadrant is of the highest value as it means working to the highest level of rigour (i.e. the quest for understanding) within a high standard of relevance (i.e. use considerations). The pragmatist researcher shares Stokes' view and believes in the benefits of bridging theory and practice. This study is based in Pasteur's Quadrant as the aim of the study was to understand the deeper processes involved in the design, use and functionality of SCGs and to make a contribution to the explanatory body of knowledge in the field of SCGs, whilst using this knowledge to improve the practical design of SCGs by providing a framework for the design of SCGs with controlled pressure. This study took on a use-inspired basic scientific approach (Stokes, 1997). It is believed that through this the study outcome would be a balanced approach between research and applicability.

4.2.2.2 Interdisciplinarity

Interdisciplinarity is defined as "a cognitive process by which individuals or groups draw on disciplinary perspectives and integrate their insights and modes of thinking to advance their understanding of a complex problem with the goal of applying the understanding to a real-world problem" (Repko et al., 2014:28). The concept of interdisciplinarity differs from multidisciplinarity, as it not only considers insights from two or more different disciplines individually, but integrates views from different disciplinary perspectives and tries to find common ground (Repko et al., 2014). Next to the integration of different disciplines, complexity is a key aspect of interdisciplinary studies. The multifaceted research problem is seen in its whole complexity, rather than simplified as is common in single-disciplinary enquiries. As a result, the insights gained through interdisciplinary studies are believed to be more comprehensive than insights from a single-disciplinary approach (Repko et al., 2014).

Interdisciplinarity is a concept that fits well into a pragmatist research study, as knowledge is seen as open-ended and hard to define because of the many relationships between elements and the dependency on context (Welch, 2011). Interdisciplinary research has the potential to create understanding among different disciplines, as interdisciplinary researchers try to see the research problem from each disciplinary perspective in order to synthesise knowledge to create a holistic understanding of complex problems (Boix Mansilla, 2005; Welch, 2011).

An interdisciplinary research approach was critical for this study due to the complexity of the design of SCGs and the many elements that can affect the functionality of SCGs. The topic of SCGs is multi- and interdisciplinary in nature. So far, researchers have approached the topic from the viewpoint of a single discipline. The researcher believes that disciplinary views are biased, but that evaluation and synthesis of different views can lead to a more comprehensive, less biased understanding of SCGs and their design requirements. Interdisciplinarity is seen as an applied orientation that builds bridges between the different disciplines related to SCGs. This study attempted to analyse the relevant disciplinary perspectives and integrated their insights to produce a more comprehensive understanding of SCGs and the problem under investigation.

Klein (2004) described two different models of interdisciplinarity: critical and instrumental interdisciplinarity. Critical interdisciplinarity interrogates existing structures of knowledge, whilst instrumental interdisciplinarity is concerned with practical problem solving (Repko et al., 2014). According to Welch (2011), critical interdisciplinarity corresponds to the post-modern school of thought, whilst instrumental interdisciplinarity corresponds with the pragmatist paradigm. Critical and instrumental interdisciplinarity are seen as two different approaches to interdisciplinarity at different ends of the spectrum. However, when viewed through the research lens of this study, the two approaches are not mutually exclusive. It has been established that the researcher's perspective is that of pragmatism and the study has been placed within Pasteur's Quadrant. As a consequence, this study was concerned with both rigour and relevance and was motivated by the goal of creating theoretical and practical knowledge. This was done through cross-examination of existing knowledge on SCGs and by trying to solve practical problems related to the design of SCGs. Based on this assumption, it is argued that this study applied both a critical and instrumental interdisciplinary approach.

4.2.2.3 Design Science Research

"Scientists try to identify the components of existing structures. Designers try to shape the components of new structures." (Alexander, 1964:130). Design Science Research is problem-based research that applies a systematic process, designing in scientific ways to create contributions to knowledge (Cross, 1993; Cantamessa, 2003; Offermann et al., 2009). It is a fairly young branch of research, offering a variety of approaches, which makes it applicable in many disciplinary fields (Cantamessa, 2003). Various Design Science Research approaches have developed over the years, resulting in a number of different terminologies used to describe it, such as 'development research' (van den Akker, 1999), 'design and development research' (Ellis and Levy, 2010), 'design experiment' (Brown, 1992; Reeves, 2000) and 'formative research' (Newman, 1990) in education and instructional research. The term Design Science Research stems from the disciplines of engineering (Eder, 1998) and information systems (Hevner, 2007; Offermann et al., 2009; Geerts, 2011). Despite the various terminologies, the common aspects of Design Science Research are that an artefact (e.g. a product, model, tool or process (Richey and Klein, 2005)) is created and that the process entails research, not solely product development (Reeves, 2000; Ellis and Levy, 2010). The difference between research and product development lies in the identification of an original contribution to the knowledge base of foundations or methodologies that is achieved by research (Hevner et al., 2004; Ellis and Levy, 2010).

Design Science Research contributes to both theory and practice, which are believed to be reciprocally linked, and thus is in agreement with the principles of the pragmatist paradigm (Hevner et al., 2004; Wang and Hannafin, 2005; Hovorka, 2009; Goldkuhl, 2012; Dalsgaard, 2014). Design Science Research strongly emphasises relevance of research to the application environment, rather than research for research's sake. This also goes in line with Stokes' (1997) recommendation of working in Pasteur's Quadrant. The synergy between practice and research in Design Science Research is believed to generate principles that inform not only the artefact design, but also the thinking and actions of researchers and designers (Wang and Hannafin, 2005).

Even though no artefact was designed and applied as part of this study, many of the principles of the Design Science Research concept have influenced the design of this research, as it reflects the researcher's view on problem-based design-related research.

The described concepts of Pasteur's Quadrant, Interdisciplinarity and Design Science Research, together with the pragmatist philosophical perspective have shaped the approach of this study and the methodological framework of the study, which is described in the next section.

4.3 Methodological Framework

To develop a methodological framework for this study, methodologies applied in existing studies on SCGs were reviewed. However, as most of these studies were conducted in the sports science field, other related fields had to be consulted in order to find suitable methodological approaches that would lead to the achievement of the aims of this study. These fields included consumer studies, general textile and garment analyses, medical compression studies, measurement surveys, evaluation studies and design research studies. Since these studies stem from a large array of disciplines, their methodological approaches were fairly varied. Due to the complexity and interdisciplinarity of this study, a methodological framework that worked for the specific research aims of this study, was developed. This approach was rooted in the pragmatist research philosophy of this study, which supports the use of methodologies and methods that are best suited to the research questions and context (Nastasi et al., 2010). The developed methodological framework worked as a research base, supporting the systematic approach of this study.

4.3.1 Overview of Methodological Framework

The methodological approach of this study is based on induction. Inductive research develops theory as a result of data collection and analysis, in contrast to deductive research, which uses data collection and analysis to test pre-defined theories or hypotheses (Saunders et al., 2012). An inductive approach was considered the preferred option for this study due to the limited existing research on the design of SCGs. It allowed the exploration of the field of SCGs through analysis of the theoretical knowledge base and the practical use environment to develop structured thinking, which was synthesised to define a design framework.

The basic scaffolding of the methodological framework was based on three key stages: analysis, evaluation and synthesis. These terms were defined by Bloom (1956) in his Taxonomy of Educational Objectives, which the author developed to enable the use of commonly understood language for educational objectives (Krathwohl, 2002). The taxonomy defines analysis broadly as taking apart the known, evaluation as making judgements, and synthesis as putting things together differently (Bloom, 1956). Whilst Bloom saw evaluation as being the highest level above synthesis in his hierarchical taxonomy, this study viewed synthesis as the most complex element of the taxonomy, as synthesis involves the creation of something new. This view is supported by Anderson and Krathwohl (2001), who developed a revision of Bloom's Taxonomy, which incorporates this change in order to show that creation is the highest form of learning. Anderson and Krathwohl (2001) re-named synthesis to 'create', which highlights the element of newness. In the case of this study, the newness lay in the development of new knowledge in the form of a design framework. The understanding of the researcher of these terms is summarised in Figure 4.2, which also shows how the aims of this study fit into the three categories.

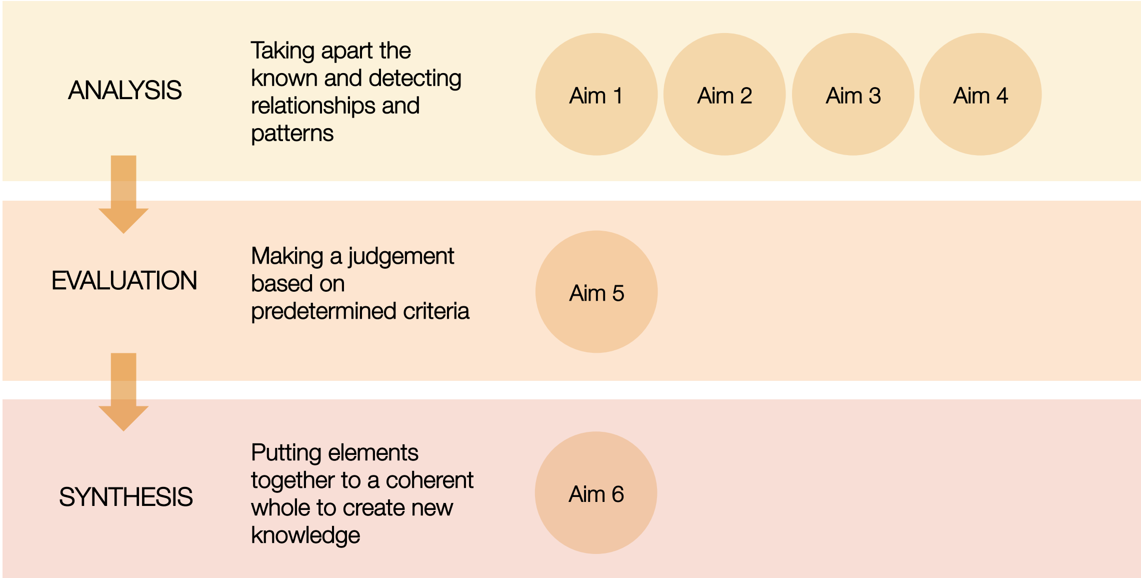


Figure 4.2: Three key stages of this study (loosely based on Bloom, 1956; Anderson and Krathwohl, 2001)

Figure 4.2 builds the basic scaffolding for the methodological framework of the study. To further develop the methodological framework, the study was divided into four phases:

- Phase I: Existing Research,
- Phase II: Users and Sports Compression Garments,
- Phase III: Pressure Prediction,
- Phase IV: Design Framework.

In line with the pragmatist perspective, it was important that both the theoretical knowledge base and the ‘real world’ would inform this study, whilst also benefitting from the study. With this in mind, the final methodological framework (see Figure 4.3) was a closed system with contributions from the theoretical knowledge base to increase rigour and contributions from the ‘real world’ to increase relevance. The four different research phases were allocated to the analysis, evaluation and synthesis stages of the study. Phases I and II were part of the analysis stage of the study. They formed an as-is analysis of the current situation of SCGs by extracting information from existing research and theories as well as from the application environment and its users. The analysis stage was aimed at creating a better understanding of the current state of SCGs and allowed the identification of problems and opportunities with SCGs in research and practice. A detailed as-is analysis is a common approach to initiate a study in Design Science Research

(Goldkuhl, 2012). The findings of Phases I and II were fed into Phase III, which formed the evaluation stage of the study. Phase III was concerned with the evaluation of virtual fit for pressure prediction. The findings from all previous research phases eventually fed into Phase IV, which represents the final synthesis stage of the study, where design principles and a design framework were defined. At the end of the synthesis stage the design framework informed the 'real world' to improve product development and new theoretical knowledge, including design principles, were added to the knowledge base, closing the loop of the methodological framework. Using the developed methodological framework, the study demonstrated a high level of rigour and relevance as theory and practice both fed into the research with tangible contributions to both fields at the end of the study, closing the gap between academic and industry research on SCGs. Working within the developed methodological framework enabled working within Pasteur's quadrant and went in line with the pragmatist foundation of the study.

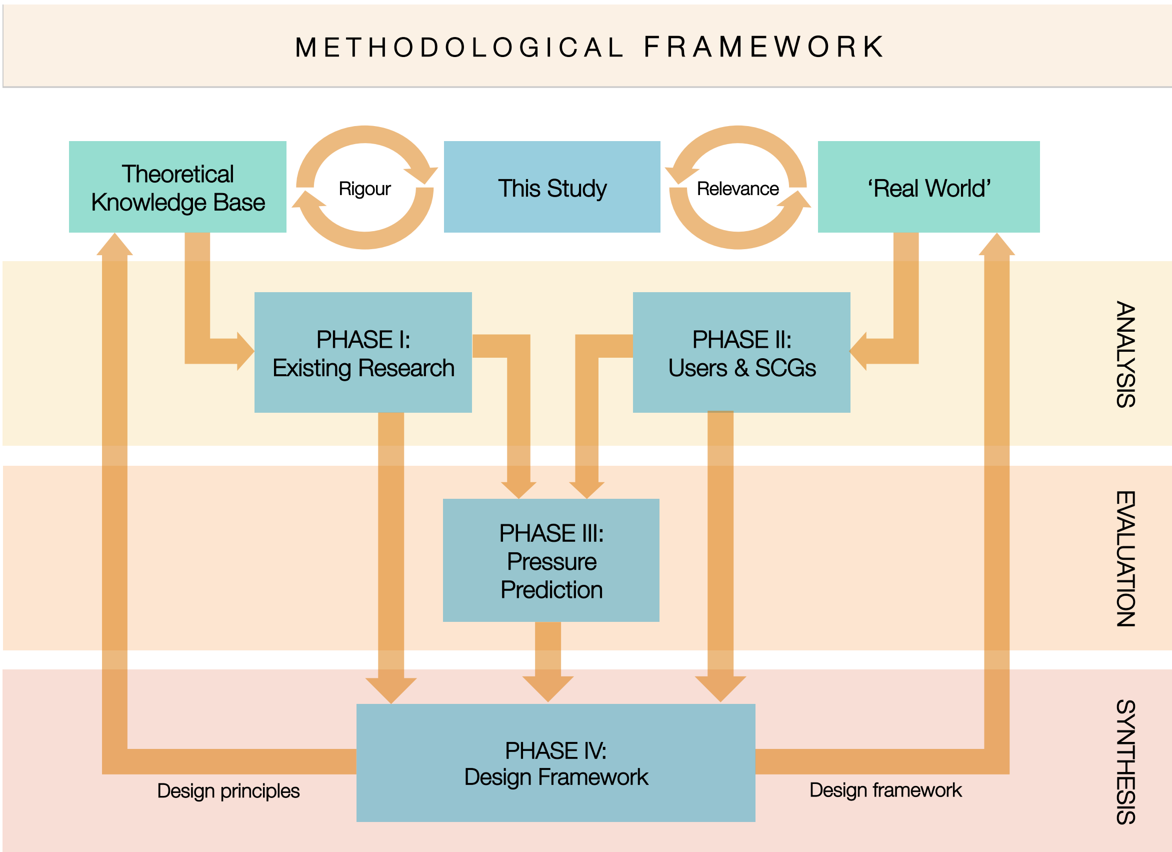


Figure 4.3: Methodological framework of this study (loosely based on Hevner et al., 2004)

4.3.2 Limitations of Methodological Framework

The methodological framework of this study described in the previous section has been designed for the specific research problems and context of this study. As a result of the pragmatist research philosophy, which constitutes that the external reality is transient, the knowledge developed in this study may be perishable in the constantly changing world (Hevner et al., 2004). The design principles resulting from this study were developed for a particular problem and environment and may not be generalisable to all design situations of SCGs. Design and product development processes are complex and change with time (Björk and Ottosson, 2007), hence proving that design principles are true or false is difficult (Andreassen, 2003). However, the focus of this study was not to develop theories that are absolute truths, but to structure thinking about the design of SCGs and offer a productive proposal on how the research and practice related to the design of SCGs could be improved. This view is rooted in pragmatism and supported by Östmann (2005), who stated that the strength and value in theory is not necessarily in “fixed truth”, but in “triggering new insights and development” (Östmann, 2005:8).

The development of the methodological framework of this study was critical as it clarified what this study was aiming for: the creation of new knowledge for the benefit of SCG researchers and designers. This new knowledge is seen as a ‘temporary truth’, which is hoped to initiate discourse in the field and might be expanded by future research. These considerations are important for the research strategy described in the next section.

4.4 Research Strategy

The direction for the research strategy was already given by the methodological framework, however, detailed strategies, methods and tools had to be selected for each research phase in order to achieve the research aims.

4.4.1 Overview of Research Strategy

Working within the developed methodological framework (Figure 4.3), it was essential to use a quantitative approach due to the technical nature of the design of SCGs with controlled pressure, which was mainly concerned with the measurement of variables, rather than subjective opinions. It was deemed appropriate to select a multi-method quantitative approach for this study in order to fulfil the study's aims because of the complexity of the research study and aims. This approach was rooted in the ideas of Design Science Research, which encourages scientific ways of designing (Cross, 1993). Multiple data collection methods were used to address the different research aims and related research questions, including an online survey, fabric and garment analyses, and wearer trials (WTs), which were conducted in a cross-sectional time horizon. Even though an inductive approach is less common for multi-method quantitative studies, it was the preferred approach for this study, as not much was known about the design of SCGs. An inductive approach allowed the integration of a broad range of concepts relating to the complex topic of SCGs.

Figure 4.4 presents an overview of the research strategy indicating relations to the research aims of the individual stages. The research design was divided into the four key phases that had already been defined as part of the Methodological Framework (Figure 4.3) and also featured the analysis, evaluation and synthesis stages.

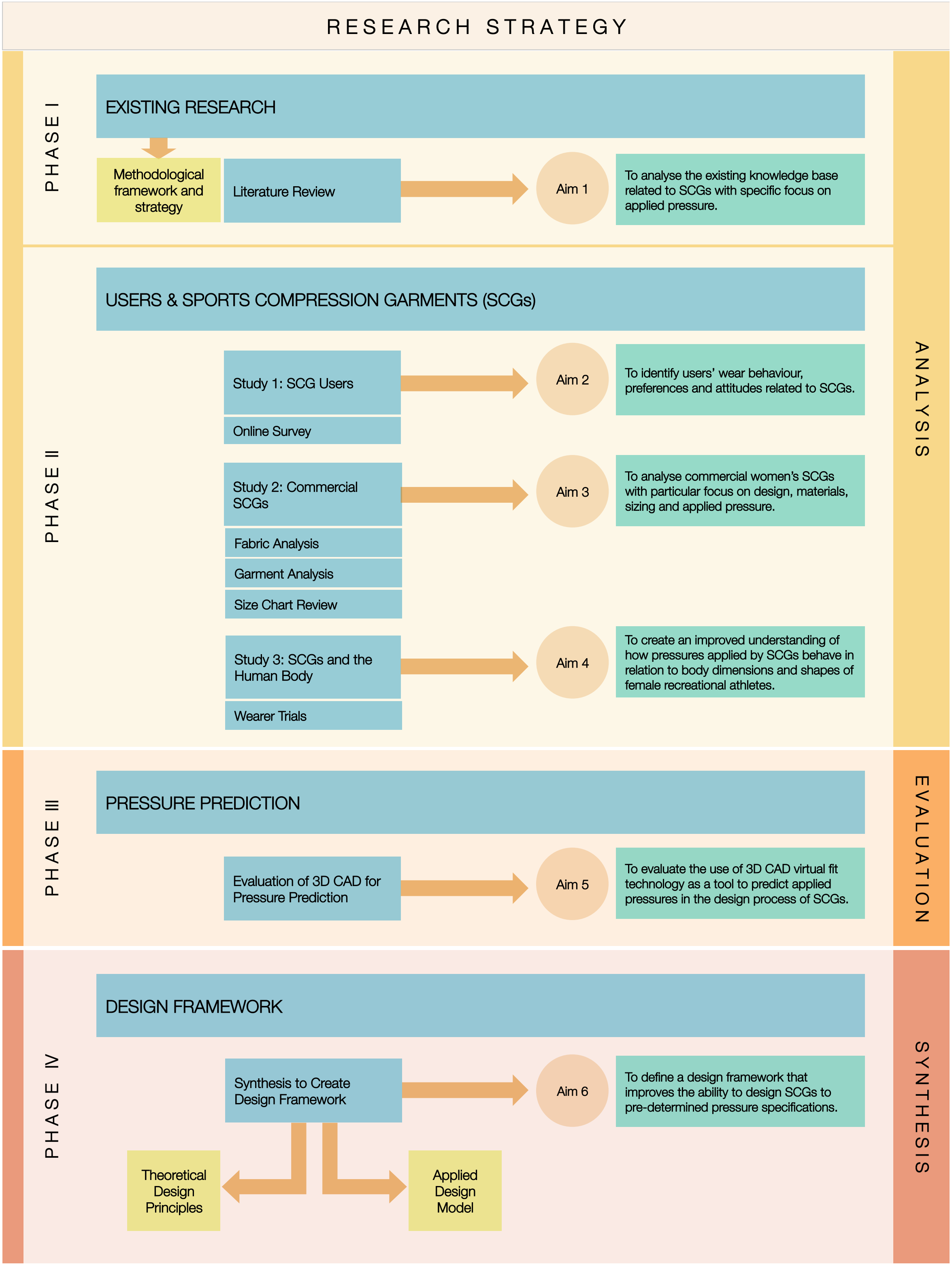


Figure 4.4: Research strategy of this study

Phase I: Existing Research

Analysing the broad theory base related to SCGs is critical to put the research into context and to establish the scope and boundaries for the study. This was especially true for the interdisciplinary topic of this study. A conceptual model of related research topics was developed and a critical review of related literature identified knowledge gaps and problems with current research as well as factors influencing the design development of SCGs. This knowledge informed the subsequent research phases and was critical for the researcher's interpretation of data in this study. Phase I fulfilled Aim 1 of the study.

Phase II: Users & Sports Compression Garments

Phase II was the primary data collection phase of the study and was related to the 'real world'. By empirically assessing the situation of current SCGs and their users, it was possible to identify 'real world' problems with SCGs. Whilst Phase I provided input from the theoretical knowledge base, the purpose of Phase II was to gain practical input from users and the environment. These 'real world' findings were critical to the pragmatist approach of this study. The methodological approach of this study demanded theoretical input as well as practical input.

Phase II - Study 1: SCG Users

In support of user-centred design, the user was considered to be the ideal starting point to gain access to the topic of SCGs. An explorative approach using an online survey was applied to obtain user insights. As existing studies had mostly ignored user needs and perceptions and there were no known published studies using surveys in the context of SCGs, a new questionnaire was developed. The survey was conducted using the online software Qualtrics and the responses were statistically analysed using IBM® SPSS® Statistics (Version 21). The findings of the survey fulfilled Aim 2 of the study.

Phase II - Study 2: Commercial SCGs

In Study 2, the focus shifted from the user to the product. In order to get an understanding of the properties of commercial whole-body SCGs, women-specific long sleeve tops and long tights from the premium brand Skins were analysed in sizes Small, Medium and Large. One set of garments was deconstructed and the fabrics analysed. The garments' design and construction were examined, technical drawings were created and the patterns were reconstructed. The textile testing was conducted according to test standards and established approaches were applied for the garment analysis. The resultant knowledge was critical when analysing the pressures applied by SCGs. The quantified fabric and garment properties were also needed for the subsequent evaluation of virtual fit for pressure prediction (Phase III).

Size charts of the most popular SCG brands were reviewed and the SCGs under investigation were measured in order to identify principles for grading. Different sizing methodologies were compared and evaluated. The findings of the analysis of the commercial SCGs fulfilled Aim 3 of the study.

Phase II - Study 3: SCGs and the Human Body

Study 3 focused on the relationship between the user and product. Therefore, WTs with the whole-body SCGs from Study 2 were conducted. A three-dimensional (3D) body scanner (Size Stream, Cary, NC, USA) was used to capture participants' body measurements in underwear and whilst wearing SCGs. Pressures applied by the SCGs were mapped using PicoPress® (Microlab, Padova, Italy) sensors. The measured compression values were used for the evaluation of virtual fit for pressure prediction in Phase III by verifying that the predicted pressures match actual pressure measurements (PMs). A user feedback questionnaire was used to obtain perceptual feedback. The findings from the WTs led to the fulfilment of Aim 4 of this study.

Phase III: Pressure Prediction

Phase III was an evaluation of the use of virtual fit technologies for pressure prediction. The 3D computer-aided design (CAD) programme Optitex (EFI Optitex, Israel) was used for this purpose. The garment parameters obtained in Study 2 and the anthropometric data and physical pressure data from Study 3 of the preceding research phase were used for the evaluation. The evaluation of virtual fit technologies for pressure prediction fulfilled Aim 5 of the study.

Phase IV: Design Framework

The findings from Phases II and III were synthesised with those from the theoretical knowledge base (Phase I) in order to translate them into principles for the design of SCGs. Theoretical design principles that could guide future research were defined as well as a design framework that facilitates the development of SCGs.

The following sections describe the four different phases of the study in detail outlining the research methods and tools applied to achieve the research aims.

4.4.2 Phase I: Existing Research

The research problem outlined in Chapter 1 of this study served as a starting point for this research project. A comprehensive and critical review of existing literature was needed to support the assertions made about the justification and significance of the study and to fulfil Aim 1 of this research (see Figure 4.5). A literature review was also important for the selection of appropriate research methodologies and methods for the study, as methodologies used by existing, similar studies could function as guidelines. The literature review, thus, served as the foundation upon which the research was built (Ellis and Levy, 2010).

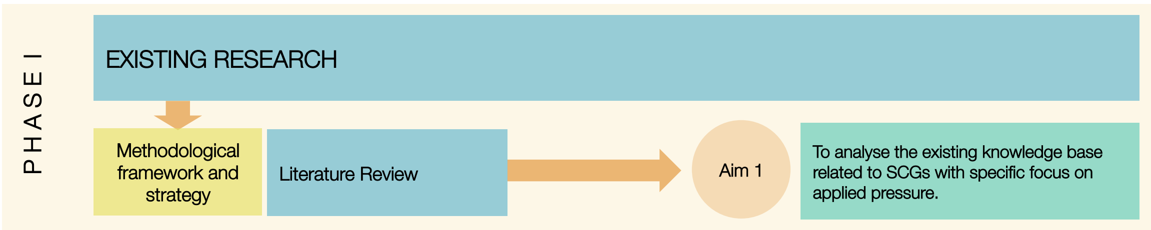


Figure 4.5: Phase I of this study

As Phase I of this study, the literature review was part of the analysis stage of the study and aimed to give an accurate profile of the theoretical knowledge base of SCGs. The initial literature search put the research into context and helped to further specify the research problem and knowledge gap. Some of the general questions that guided the initial literature review were derived from Hart (1998):

- What are the key sources on the topic?
- What are the origins and definitions of the topic?
- What are the key theories, concepts and ideas?
- What are the major issues and debates about the topic?
- What are the main questions and problems that have been addressed to date?

To identify current thinking and key concepts in the field of SCGs, it was necessary to explore a wide range of existing publications. Suitable databases were identified and initial literature searches were conducted using Boolean logic. Databases used, search terms and numbers of search results are listed in Appendix G.

The identified studies were scanned and broadly divided into different themes. The reference lists of studies that were the most relevant to the research problem at hand were searched to identify further relevant studies. Database search alerts were set up, so that the researcher was kept up-to-date with the latest research on SCGs and could continually add the latest literature to the literature review.

As SCGs were a fairly new branch of research, which was rooted in the medical and sports science fields, many topics related to the design of SGCs had not been researched in the context of SCGs and more general searches on these topics were required to inform the study. A list of key words for further literature searches was, therefore, created and is included in Appendix G.

During the critical review of literature it became apparent that there was an abundance of research on the functionality of SCGs mostly conducted by researchers from the sports science field. These studies tested the effects that various types of SCGs had on exercise performance or post-exercise recovery of their study participants. Repeatedly problems with the study design were noticed when reviewing the studies as pressure levels and occasionally garment types were not reported. It was decided to perform a detailed critical review of available studies on the functionality of SCGs to get an overview of the current state of research. This was hoped to potentially lead to conclusions on the physiological effects that SCGs could have on the wearer, which was critical knowledge for the researcher. Studies included in the review had to be original research studies published in English with healthy human participants wearing SCGs during and/or after exercise. Table 4.1 summarises the study features that were collated as part of the critical review.

Table 4.1: Study features collated for the critical review of existing literature measuring the functionality of SCGs

Study details:	Reference
	Year
	Background of authors
	Focus of study (performance, recovery or kinematics/proprioception)

Characteristics of participants:	Sample size (number of participants wearing SCGs)
	Gender (male/female)
	Average age (years)
	Health status
	Training status (not trained, recreational athlete, competitive athlete, elite athlete)
	Trained for exercise to be undertaken (yes/no)
Characteristics of compression garments:	Type of garment
	Number of different garments tested
	Brand name and garment model
	Level of pressure applied to body (mmHg; graduated - yes/no)
	Pressure determination (measured, relying on pressure estimated by supplier, calculated)
	If measured: PM location(s)
	Fit methodology (body measurements taken, size chart followed, PMs)
Study protocol:	SCG worn during exercise (yes/no)
	SCG worn during recovery (yes/no)
	Length of time worn post-exercise
	Type of exercise
	Experimental protocol
	Other treatment received
	Control trial (yes/no)
Results:	Performance evaluation (measured variables and effects)
	Recovery evaluation (measured variables and effects)
	Motor function evaluation (measured variables and effects)
	Measures of perception (measured variables and effects)
	Effects on performance (significant positive effect, some positive effect, no positive effect)
	Effect on recovery (significant positive effect, some positive effect, no positive effect)
Comments	(added by the researcher)

Studies reporting pressure values were analysed in more detail by calculating frequencies and identifying pressure ranges for the different study outcomes.

The literature search, review and analysis procedure applied in Phase I of this study is summarised in Figure 4.7. The extensive literature review provided a solid foundation for the methods and direction of this study. The systematic approach used for the literature review increased the validity of the findings of this research phase.

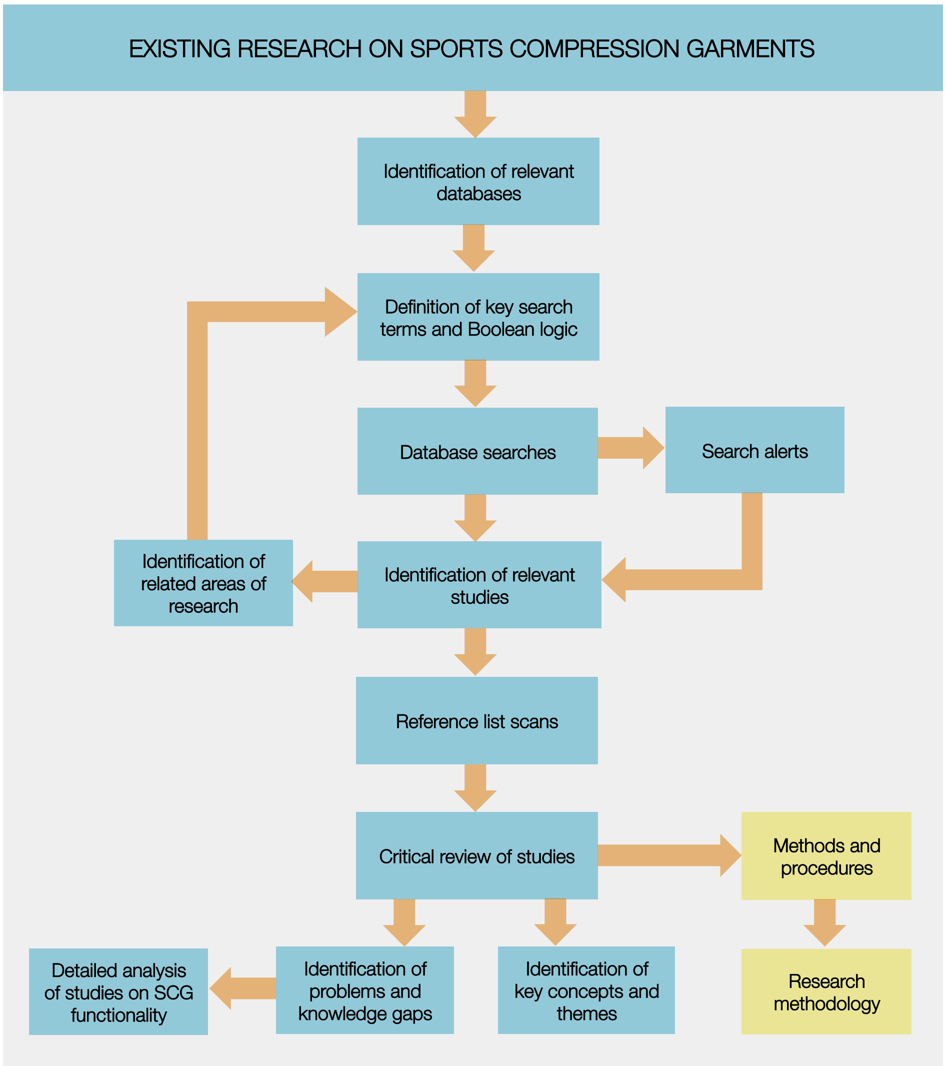


Figure 4.6: Literature review strategy of this study

The literature review was divided into two key areas, firstly SCGs as ergogenic aid to support sports performance and recovery (Chapter 2), and secondly, aspects related to the design of SCGs (Chapter 3). The overall thread that runs through both chapters is the topic of pressure as it is what differentiates SCGs from conventional sportswear and clothing. Due to the limited research on SCGs from a clothing perspective, many of the garment concepts related to SCGs (e.g. design, fit, sizing) originated from general clothing research and, thus, did often not relate to the specifics of skin-tight knit garments. These concepts were refined as much as possible by the review of broad literature.

A conceptual model of related research topics was developed (Figure 5.1) and the critical review of related literature identified knowledge gaps (Figure 5.2) and problems with current research (Chapter 5).

4.4.3 Phase II: Users and Sports Compression Garments

Whilst Phase I provided input from the theoretical knowledge base, the purpose of Phase II was to gain practical input from users and the environment (refer Figure 4.8). Phase II was the primary data collection phase of the study. By empirically assessing the situation of current SCGs and their users, it was possible to identify 'real world' problems with SCGs. Phase II was divided into three separate studies. Study 1 focused on SCG users. The focus then shifted to the product itself in Study 2, where commercial women's SCGs were analysed. Study 3 combined the users and SCGs in WTs with commercial SCGs. The research methods and tools used in the three studies are outlined in the following subsections.

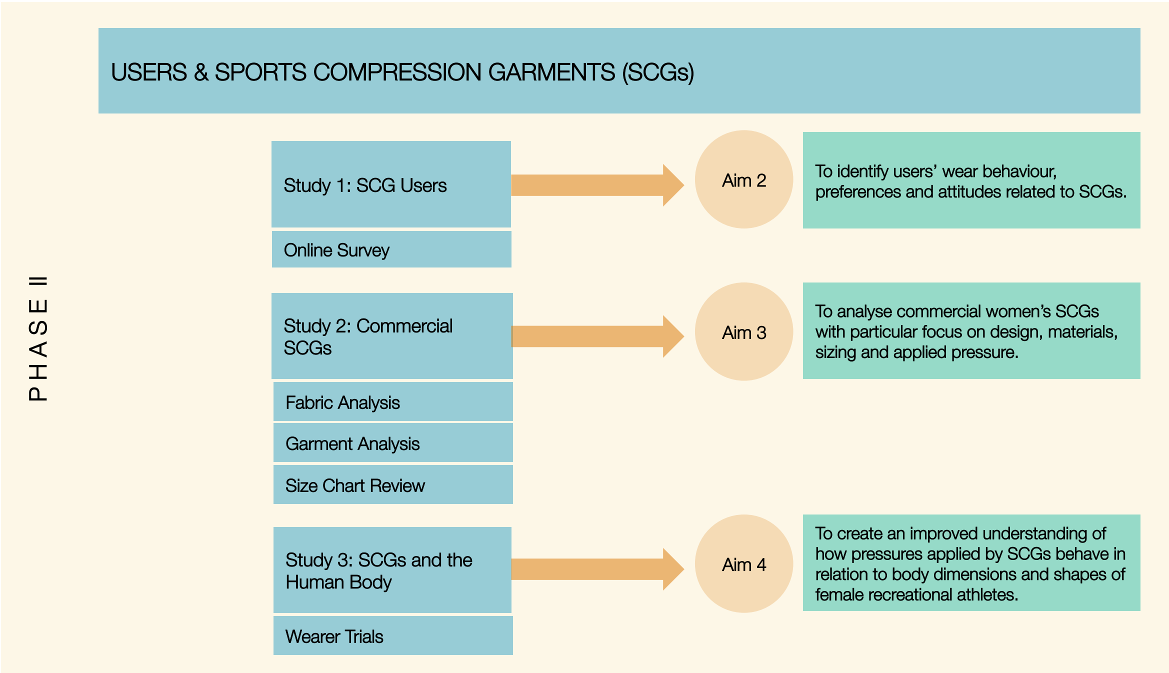


Figure 4.7: Phase II of this study

4.4.3.1 Study 1: Sports Compression Garment Users

User experiences with SCGs were central to the analysis of the as-is situation that initiated the research and added relevance to the study. Users can provide information about their product preferences and wear behaviour, which is critical for designing SCGs. Further, understanding users' perceptions of SCGs would lead to insights into psychological effects of wearing SCGs.

Online Survey

A questionnaire was chosen as the research instrument to explore the consumption habits and opinions of SCG users, as it is the preferred survey instrument when relatively simple quantitative information is to be collected from a large sample (Gratton and Jones, 2010). Questionnaires are an effective instrument to explore, describe, explain or evaluate people's attitudes, beliefs, past behaviour and opinions (Flynn and Foster, 2009). Quantitative surveys with closed questions are easy to process and analyse (Gillham, 2008; Gratton and Jones, 2010). Data is collected and stored with a minimum of intervention by the researcher, which reduces the risk of errors (Bryman, 2016).

An online survey was chosen as the preferred instrument for this study, as it is a fast and economical way of conducting surveys, allowing the researcher to easily reach geographically dispersed members of athletics clubs (Gillham, 2008; Gratton and Jones, 2010; Upcraft and Wortman, 2015). Online surveys also offer the possibility to skip subsequent questions based on question responses with the skip patterns being invisible to the survey respondents (Leedy and Ormrod, 2013; Robson and McCartan, 2016). Some evidence indicates that online surveys result in fewer unanswered questions (Bryman, 2016) and that they yield data comparable to those obtained through face-to-face contact (Gosling et al., 2004). An online survey was, thus, a well-suited instrument for obtaining an overview of SCG users wear behaviour, product preferences and attitudes towards SCGs. An online questionnaire with mainly closed questions was applied for this quantitative study.

Survey Development

As existing studies on SCGs have mostly ignored user needs and perceptions, no studies using surveys in the context of SCGs could be identified. Survey instruments used in other fields, such as sports psychology, did not meet the purpose of this study. Consequently, a new online survey had to be developed. The survey development followed a systematic approach as shown in Figure 4.9.

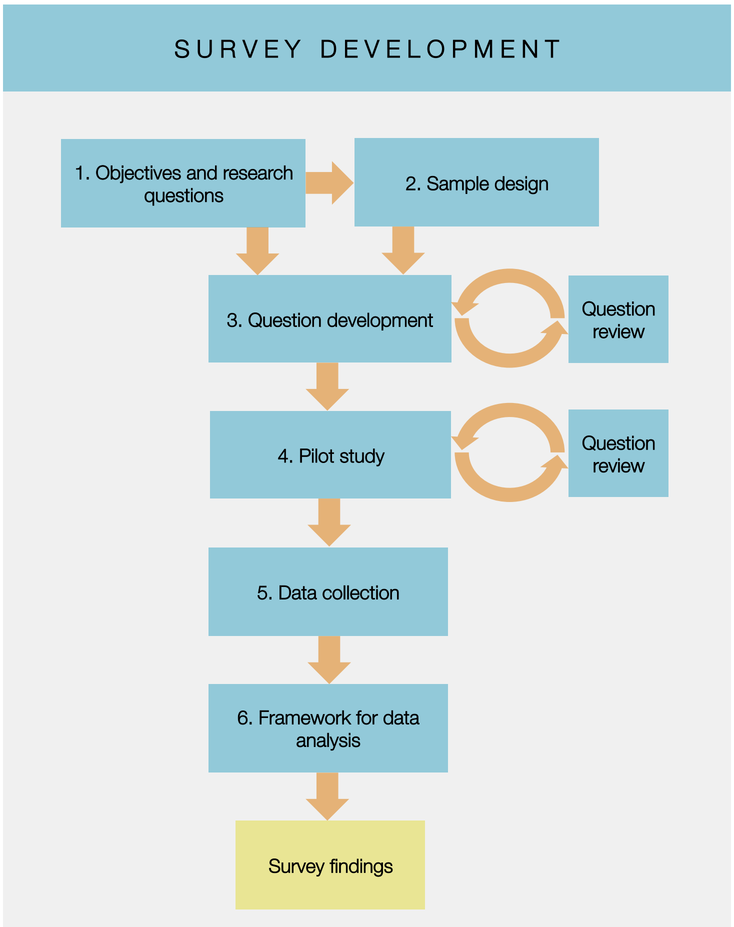


Figure 4.8: Survey development strategy of this study (adapted from Gratton and Jones, 2010; Bryman, 2012)

1. Objectives and Research Questions

The aim of the study was to identify user-centred factors that are critical for the design of SCGs. These factors would later feed into the design principles and framework for SCGs. No existing research on SCG consumption or user perspectives could be identified. As was highlighted in section 3.2, identifying users' functional, expressive and aesthetic needs is essential for the design of functional clothing. In relation to user experiences with SCGs functional needs are concerned with the way SCGs are used and the use environment, expressive needs are related to perceptions and beliefs, whilst aesthetic needs are concerened with personal product preferences. Consequently, three themes emerged that the survey had to address: wear behaviour, attitudes towards SCGs and product preferences. In addition to exploring respondents' functional, expressive and aesthetic user needs, it was important for the analysis of the as-is situation to establish the respondents' opinions on existing commercial SCGs. This enabled the identification of potential problems or discrepancies between current SCGs and user needs. The objectives of the survey were defined as follows:

1. To identify the way the survey respondents use SCGs.
2. To determine the survey respondents' attitude tendencies towards SCGs.
3. To identify needs and product preferences of the survey respondents.
4. To establish whether commercial SCGs fulfil the needs and expectations of the survey respondents.

Research questions were developed around the three defined themes. In addition, it was critical to understand variations between genders and different user characteristics. The online survey aimed to find answers to the following research questions:

- Wearer behaviour:
    - What type of SCGs do the respondents wear and how do they use them?
- Attitudes towards SCGs:
    - Do SCGs have psychological effects on the respondents (e.g. self esteem)?
    - Do the respondents believe that SCGs can enhance their performance and/or recovery?
- Product preferences:
    - What do the respondents like about SCGs?
    - Are commercially available SCGs satisfactory for the respondents?
- User variability:
    - Could different user characteristics affect the way respondents use SCGs or the way they think about them?

These research questions were critical for the design of SCGs and it was hoped to get insights into psychological effects of wearing SCGs (e.g. placebo effect, body image satisfaction) by exploring attitudes and perceptions. These consumer insights would enhance the theoretical knowledge base and increase the study's commercial relevance.

2. Sample Design

Before developing the survey questions, it was important to define the sample for the online survey. This allowed tailoring the questions to the sample. As there was nothing known about SCG users due to a lack of existing research, the aim of the survey was to capture the opinions of a large variety of different users. This would allow the analysis of user variability based on different user characteristics. Hence, both male and female SCG users were included in the sample, despite the focus of this research on women's SCGs. Based on women-specific design requirements mentioned in literature (refer 3.2.3), it was important to identify any potential differences between female and male SCG users.

The sampling procedure for this study was based on a combination of purposive and volunteer sampling. Purposive sampling seeks participants based on specific characteristics related to the research questions (Smith, 2010; Leedy and Ormrod, 2013). Athletics clubs and certain online forums were chosen to distribute the survey, as it was believed that the number of SCG users is higher among members of these groups compared to the general population. The athletics clubs included in the sample were limited to the clubs listed on the British Athletics website (http://www.britishathletics.org.uk). Volunteer sampling meant that only people who were willing to volunteer participated in the survey.

Even though the described sampling precedure is non-random, it was regarded as an appropriate method, as without an available sampling frame the population of SCG users was hard to access and the overall size of the SCG user population was unknown. The described approach is supported by Hewson and Laurent (2008), who suggested posting invitations to relevant online message boards, mailing lists or websites when no sampling frame is available. When using this approach, the representativeness and response rate of the final sample are unknown, however it is a good approach to target groups with specific interests (Bryman, 2016). A minimum of 100 responses from SCG users was targeted.

3. Question Development

Formulating questions is a crucial part of developing questionnaires. Online surveys offer a one-off chance of data collection, therefore it is critical to have a well-designed survey (Gratton and Jones, 2010). The wording of survey questions is crucial in all questionnaires, but particularly in online surveys, as they are self-administered surveys without the opportunity for respondents to question any ambiguity (Gillham, 2008). Consequently, the survey questions were carefully formulated using simple and clear language. Attention was put to the word use in order to avoid loaded questions and to make questions as self-explanatory as possible. All questions were scrutinised to detect any potential ambiguous wording or implied meaning and were checked for face validity.

The research questions defined in stage 1 of the survey development were used as a starting point to develop survey questions. More focused questions that would provide the information needed to answer the research questions were formulated and the most suitable question types that would lead to the required data were selected as documented in Appendix H. The collated details in Appendix Table H-1 were then used to define the final survey questions and ensured that the survey would collect the information required to answer the research questions.

Closed question types were mainly used in the survey. Reply options for closed questions need to be chosen carefully, as they could direct respondents' thoughts by providing answer choices (Schwarz, 1999; Oppenheim, 2000; Fisher and Buglear, 2010). An 'other (please specify)' option was added where appropriate to avoid limiting respondents' thoughts. To ensure that respondents had the chance to express additional views, an open-ended question was added as closing question. The survey instrument was also used to recruit participants for the subsequent WTs. At the end of the survey, a separate questionnaire was linked to the survey informing the participants about future WTs and encouraging them to leave their contact details to receive further information about the WTs in due course.

Attitude scales are a series of statements to which the respondents indicate their level of agreement. They are designed to measure an attitude towards a specific concept with total scores being combined for each individual (Gliem and Gliem, 2003; Gratton and Jones, 2010). In order to assess the respondents' attitudes towards SCGs, an attitude scale based on 5-point Likert scales was developed. A pool of attitude statements building an attitude scale offers a more accurate insight into respondents' attitudes than a single question (Oppenheim, 2000) increasing reliability and validity of the attitude measurement (Gliem and Gliem, 2003). Using several segments to measure the same construct is regarded as a type of triangulation (Robson and McCartan, 2016).

A new scale had to be developed, as there were no published attitude scales for SCGs, although a number of scale-based questionnaires were identified in the sports field (Harmison, 2000; Peart et al., 2005; Petroczi and Aidman, 2009; Uphill et al., 2012; Malek et al., 2014). It is common practice to use questionnaires in experimental situations in sports studies for the assessment of athletes' attitudes. Whilst the attitudes to be measured varied substantially from the attitudes towards SCGs, reviewing these studies improved the researchers knowledge on scales and the way statements should be phrased. Riemer and Chelladurai (1998) recommend a systematic approach for developing attitude scales. They suggest a three-stage process of 1) item generation, 2) primary item analysis, and 3) item revision. First a large pool of items was generated by examining the study's research questions and reading generic surveys, such as the athlete satisfaction questionnaire developed by Riemer and Chelladurai (1998). The items were then qualitatively assessed for logic and readability and were placed into two thematic categories: feelings and beliefs. Feelings represent the emotional component of attitudes, whilst beliefs are linked to the cognitive component (Oppenheim, 2000). Key emotional concepts were connected to the feeling when wearing SCGs (e.g. confidence, body image and psychological edge), whereas key cognitive concepts were linked to beliefs in the performance of SCGs. The items were then scored based on their favourability towards SCGs. Items that were fairly neutral or unclear in their favourable/unfavourable direction were removed. The list of generated items was reduced to 16 items that were believed to measure emotional and cognitive aspects of attitudes towards SCGs. A balance between positive and negative statements and statements related to feelings and beliefs was maintained.

The third stage of scale development, item revision, was conducted after the pilot study of the online survey. The revisions were based on the results of statistical analysis using Cronbach's alpha as a measure for internal consistency as recommended by Gliem and Gliem (2003) and mean inter-item correlations based on suggestions from Pallant (2013).

According to Oppenheim (2000) six to 24 items are appropriate to explore attitudes. The mix of positive and negative items in the 16-item scale was believed to increase score reliability by reducing 'lazy' responses and was thought to increase the respondents' attention. The items were ordered randomly and scored so that a high score reflected a favourable attitude towards SCGs. Results of the attitude scale question of the survey provided a general idea of the respondents' attitude towards SCGs. It further allowed grouping respondents and correlating their responses to other survey questions.

The pilot version of the online survey had 22 questions divided into four question modules: classification data, attitudes, wear behaviour and product preferences.

Once all survey questions for each survey module were finalised, decisions about the question order had to be made. Gillham (2008) suggests placing personal data questions at the start of the questionnaire, as these questions are easy to answer by respondents. However, Oppenheim (2000) argues that being asked about too personal and intriguing things can be off-putting for respondents. The researcher followed Oppenheim's (2000) proposition and decided on the following order for the question modules:

1. Wearer behaviour
2. Attitudes towards SCGs
3. Product preferences
4. Classification data

Initially, it was planned to have the attitudinal question module at the end of the questionnaire (before the classification questions). However, attitudes are always influenced by their context (Schwarz, 1999), which in a questionnaire means the preceding questions. As Schwarz (1999) highlights, it is inevitable to avoid contextual influence, but it can be purposefully used in wording and ordering the survey questions. In this case, the intention of the attitude question module was to investigate the judgements and beliefs of the survey respondents regarding SCGs. Belief can be a strong performance enhancer; therefore it was important to estimate the respondents' views on the performance of SCGs. It was further believed that placing the product preference question module in front of the attitudinal question module could alter outcomes of the study as respondents tend to respond in a way that they think is most helpful to the researcher (Schwarz, 1999). Starting the questionnaire with factual questions about the respondents' use of SCGs was believed to be the best option to ease respondents into the survey without substantially influencing the attitude question module.

4. Pilot Study

A pilot study of the online survey (*N* = 10) was conducted to scrutinise the content and unambiguousness of the survey questions, the administration of the online survey, and to conduct a dry run of the data analysis (Gratton and Jones, 2010). The attitude scale was statistically analysed to check the internal consistency of the scale. The only changes necessary to the survey were related to the attitude scale. Cronbach's alpha was 0.79 and the mean inter-item correlation 0.229. Even though these values were within the acceptable recommended limits (>0.7 for Cronbach's alpha (DeVellis, 2012) and 0.2 to 0.4 for inter-item correlations (Briggs and Cheek, 1986)), some of the individual inter-item correlations were negative. A detailed analysis of each individual scale item resulted in the deletion of 4 items and the change of wording of one item (see Appendix I).

The final result was a 12-item attitude scale with a roughly balanced proportion of positive and negative statements that were believed to measure emotional and cognitive aspects of attitudes towards SCGs. The items were randomly ordered and a maximum score of 60 reflected a very favourable attitude towards SCGs.

The time required for the completion of the online survey was monitored to assess whether the survey was too long. The average time of 11.66 minutes for the 10 respondents was seen as an appropriate time. Especially as the reduction of the attitude scale to 12 items was likely to reduce this time so that it could be expected to be around the 10-minute mark, which does not require too much time commitment from the respondents.

There was no need for another pilot study, as the changes to the attitude scale did not affect the usability of the survey. An additional question about the country of residence was added. The final version of the survey consisted of 23 questions and can be found in Appendix J.

5. Data Collection

The survey was conducted using the online software Qualtrics. The link to the online survey was emailed to the secretaries of all British Athletics Clubs and contacts of British Athletics Networks listed on the British Athletics website (http://www.britishathletics.org.uk). The email informed the recipients about the research and asked them to distribute the survey link to their members (see Appendix K). The survey link was further distributed online in selected social media groups and forums; a list of which can also be found in Appendix K. The data collection process was based on a cross-sectional design, as comparison of different groups within the sample was of interest rather than changing behaviour over time (Flynn and Foster, 2009). Survey responses were collected over a period of one month from end-September to end-October 2015.

6. Framework for Data Analysis

The survey responses were statistically analysed using IBM® SPSS® Statistics (Version 21). Once the quantitative data were organised, descriptive statistics were used to summarise results. Most variables in the questionnaire were of categorical or ordinal nature. With categorical and ordinal variables, means are meaningless; instead, medians and frequency tables were used to interpret results. Crosstabulations were used to assess variations in wear behaviour across genders. Further, non-parametric tests (chi-square test for independence, Mann-Whitney test, Kruskal Wallis test) were applied to analyse relationships. Chi-square tests for independence were conducted to identify associations between wear behaviour and product preference with the classification data (gender, age, training hours, competition level and years of experience). Mann-Whitney and Kruskal Wallis tests were performed to determine differences between respondents' attitude scores and the different classification data and responses to other survey questions (e.g. belief in effects, satisfaction levels).

The reliability of the attitude scale was checked using Cronbach's alpha and mean inter-item correlations.

Limitations of Study 1

The main criticism of surveys is that the data collected regarding behaviour and opinions cannot give information about why consumers behave or think in a certain way (Robson and McCartan, 2016). However, this quantitative study was conducted as part of an as-is analysis of the way users wear SCGs and what they think about current SCGs and as such was not intended to explore underlying reasons.

As the survey was a self-completion online survey, great care was taken in the formulation of questions and the online survey was reviewed multiple times to ensure that questions could not be misunderstood.

A common problem with questionnaires is that responses can be affected by social desirability bias (Robson and McCartan, 2016). Even though, the effect of social desirability bias in this study is believed to be small due to anonymity of responses and the nature of the research topic, the researcher considered social desirability bias when interpreting results.

A potential limitation of the study was the use of non-random sampling due to a lack of a sampling frame. However, the sampling approach taken was believed to be the most suitable to reach SCG users across the UK and is an established practice for online surveys (Hewson and Laurent, 2008).

Online surveys are always affected by sample bias (Gratton and Jones, 2010), as they are limited to people who have Internet access and have been sufficiently motivated by the research topic to complete the survey (Leedy and Ormrod, 2013; Bryman, 2016). This is, however, not seen as a problem for this study, as the online survey was targeting SCG users with an opinion on SCGs. The research does not claim that the findings from the online survey are generalisable to all SCG users. Generalisability was not the purpose of this research. The demographic characteristics of the sample and the average training status of the respondents were kept in mind when analysing the data. This was important as responses from other demographics and more professional athletes could result in different outcomes. Crosstabulations and correlations were calculated, where possible, to identify any variations across different demographics and training levels. The findings are only valid for fitness-related sports and are not generalisable to other sports disciplines, such as resistance training.

4.4.3.2 Study 2: Commercial Sports Compression Garments

Study 2 focused on the analysis of commercial SCGs for female athletes. The garments chosen were long sleeve compression tops and long compression tights from the elite series A400 of the compression sportswear specialist Skins (SKINS International Trading AG, Steinhausen, Switzerland). The brand Skins was chosen because it was the most popular brand among respondents of the online survey with 40% of SCG users stating that they usually wear Skins compression sportswear. The brand is a market leader in the premium compression sportswear sector. It heavily invests in research and development and prides itself on scientific evidence of the functionality of their SCGs carried out by independent researchers (Textiles Intelligence Limited, 2014b). Skins SCGs are endorsed by the Australian Physiotherapy Association (Skins, 2016).

The exact garments under investigation were the Skins A400 Women's Active Long Tights (article no. B33001001) and the Skins A400 Women's Active Long Sleeve Top (article no. B33001005) (refer Appendix L). One garment each was purchased in sizes Small, Medium and Large from the Skins online shop (www.skins.net/uk) with an additional set of garments acquired to be deconstructed for re-engineering and testing purposes. The analysis of these garments was threefold: firstly the fabrics were analysed, secondly the garments were examined as a whole, and thirdly the garments' size chart was reviewed and compared to other size charts of commercial SCGs. The aim of these analyses was to gain an accurate profile of the characteristics of the SCGs under investigation.

Fabric Analysis

Fabric properties play an important role in creating the clothing-body-environment. It is, therefore, important to analyse and understand fabric properties. This is especially true for sportswear, as the environment created by fabrics and clothing can impact exercise performance. The most important aspects for sportswear fabrics are moisture management and thermal balance (Venkatraman, 2015), as these properties affect comfort of the wearer. Elastic properties are especially important for SCGs, as they influence pressure delivery.

The fabric analysis had the following objectives:

1. To identify the key properties of the fabrics used in the Skins A400 compression top and tights.
2. To compare fabric properties of the Skins A400 compression garments to comparable fabrics used for compression sportswear.
3. To identify properties required for the garment simulation in Phase III of this research.

For Objective 2, four additional fabrics used for SCGs were analysed to have a point of comparison. The fabrics were provided by a SCG start-up brand.

A review of literature helped to develop knowledge on knit fabrics and textile testing. Existing literature giving specific recommendations for testing of fabrics for compression sportswear was scanned to identify textile tests (Liu et al., 2008; MacRae et al., 2012, 2016; Venkatraman, 2015). Based on the review of literature and the specific requirements and circumstances of this study, the following tests were selected for the analysis of the fabrics used in the Skins SCGs and the four fabrics from the start-up brand (see Table 4.2).

Table 4.2: Tests selected for fabric analysis

Property	Test standard	Instrument	Procedure
Area density (g/m^2)	BS EN 12127:1998	Sartorius balance (CP32025)	Place sample on balance and read weight off digital display once settled, then calculate: M = (mass of specimen in g x 10,000) / area of specimen in cm^2
Thickness (mm)	-	Shirley Thickness Gauge No. 7301 (Mitutoyo, Japan)	Press thumb trigger to release pressure foot and place sample between base and presser foot. Read thickness off dial.
Bulk density (g/cm^3)	Secondary calculation	N/A	(fabric thickness in cm x area density in g/cm^2) / 10,000
Courses/ wales per cm	-	Piece glass (Eschenbach Optik GmbH, Germany)	Place piece glass on sample and count number of courses and wales contained within 1cm.
Stitch density	Secondary calculation	N/A	S = C per cm x W per cm where S = stitch density, C = courses and W = wales.

Property	Test standard	Instrument	Procedure
Stretch and recovery	BS 4294:1968	Fryma extensiometer (Frymann & Fletcher Ltd, UK) Settings: 75mm between inside edge of clamps	Place sample in clamps and make reference marks on sample at inside edge of clamps. Gradually increase load on sample to 3kg and measure the length of the specimen 1min after application of full load. Return clamps to their original position. Remove the specimen, place it on a flat surface and after 1min from the time when the jaws were returned to their original position, measure the distance between the outside edges of the reference marks. Re-measure the distance between the reference marks after total relaxation time of 30min.
Bursting strength	BS EN ISO 13938-2:1999	TruBurst 2 Fabric Tester (James Heal, UK)	Place sample over the diaphragm so that it lies in a flat, tensionless condition. Clamp it securely in the circular holder. Place the distension-recording device into the measuring position and adjust it to the zero position. Fasten the safety cover and apply pressure to the test specimen until the fabric bursts.
Moisture management	AATCC 195:2009	Moisture Management Tester (SDL Atlas, USA)	Place sample on lower sensor with face up. Release the upper sensor until it sits freely on the sample. Shut the door and start the test.
FAST-1 compression	SiroFast-1	Compression meter (CSIRO, Australia)	Place sample under the pressure disk and move lever. Read compression off the digital display for 2g/cm^2. Add weight to pressure disk and repeat process to obtain compression for 100g/cm^2.
FAST-2 bending rigidity	SiroFast-2, BS 3356:1961	Bending meter (CSIRO, Australia)	Place sample under plate following marks as guides. Move plate back and forth ensuring that the sample moves with the plate. Bending meter indicates when measurement is complete. Read bending length off digital display.
FAST-3 extension	SiroFast-3	Extensibility meter (CSIRO, Australia)	Fix sample between clamps and add first weight on opposite side. Take extension reading for 5g/cm from digital display. Repeat with two other weights for 20g/cm and 100g/cm.

In addition to the above tests, a stress-strain curve of the main fabric used in the Skins SCGs was obtained using a Hounsfield tensile tester (H10KS, Tinius Olson, Salfords, UK) with the following settings:

- Load range: 100N
- Extension range: 400mm
- Test speed: 500mm/min

- Strain target: 200%
- Preload: 2N
- Specimen size: 50mm x 250mm

The maximum fabric extension of 200% was chosen as it was recommended by Hu and Lu (2015) and Watkins (2011) for testing of elastic knit fabrics.

Sampling

One sample each of the compression tights and tops were deconstructed to analyse the fabrics used in the garments. Five different knitted fabrics had been used in the compression tights (Fabric A, B, C, D and E), whilst four different fabric structures had been used in the compression top (Fabric A, D, E and F). The fabric samples were cut from the fabric panels of the unworn SCGs avoiding the seam edges and ensuring that the samples were cut parallel to the wales for warp samples and perpendicular to the wales for course samples. Due to limited sample availability, not all fabrics could be tested in both course and wale directions. Table 4.3 shows which tests were performed on each fabric with the number of samples stated where they varied from the test standard.

Table 4.3: Overview of tests conducted for each fabric

Test	Fabric A	Fabric B	Fabric C	Fabric D	Fabric E	Fabric F
Area density	✓	✓	✓ (4 samples)	✓	✓ (1 sample)	✓ (2 samples)
Thickness	✓	✓	✓	✓	✓	✓
Bulk density	✓	✓	✓	✓	✓	✓
Courses/wales per cm	✓	✓	✓	✓		✓
Stitch density	✓	✓	✓	✓		✓
Stretch and recovery[a]	✓	Course only (4 samples)	Wale only (1 sample)	✓ (2 samples)		Wale only (4 samples)
Bursting strength	✓ (3 samples)					
Moisture management	✓ (3 samples)			✓ (1 sample)		
SiroFAST-1	✓	✓	✓	✓	✓	✓
SiroFAST-2	Course and wale only	Course only (2 samples)	Wale only (1 sample)	Course and wale only (1 sample)		Wale only (2 samples)

Test	Fabric A	Fabric B	Fabric C	Fabric D	Fabric E	Fabric F
SiroFAST-3[b]	✓	Course only (2 samples)	Wale only (1 sample)	✓ (1 sample)		Wale only (2 samples)

a: sample width 50mm instead of 75mm
b: no bias samples

Sufficient amounts of fabric samples from the start-up brand were available, so that all tests could be conducted with these fabrics. The test specimens were cut following the applied test standards.

The tests were performed in a controlled laboratory with relative humidity of 65 ± 4% and temperature of 20 ± 2°C in line with the relevant British Standard (British Standards Institution, 2011) to maintain reliability of results. All samples were conditioned in this environment for at least 24 hours and were tested in their relaxed state.

The knit structure of the fabrics was determined with a piece glass and a digital microscope (Dino-Lite Pro, Taipei, Taiwan; magnification: 10-70x). Microscopic images were captured from the technical face and technical back of the fabrics.

3D CAD programmes use their own algorithms to simulate cloth. As discussed in section 3.6.3.2, some programmes used to offer the possibility to convert fabric data obtained by FAST into the 3D CAD programme's own simulation algorithm. Since FAST was originally developed for woven fabrics, the system is not well suited for knitted fabrics with high levels of stretch. The maximum stretch value that can be measured by SiroFAST-3 (test for extensibility) is 20.4%, a value that is easily exceeded by elastomeric fabrics used in SCGs. However, the tests were included here due to the potential compatibility with 3D CAD programmes.

Garment Analysis

Together with fabric properties (MacRae et al., 2016), the design and construction methods of garments are critical to determine the functional performance of garments in terms of utility and durability (Brown and Rice, 2014).

The garment analysis involved the analysis of design, construction and dimensions of the Skins SCGs. This information was needed to analyse and better understand results from the subsequent WTs and review of SCG sizing. To get an initial idea of the pressure levels and distribution delivered by the SCGs, the pressures applied by the SCGs to a mannequin were measured. The garment design properties were also needed for the simulation of the SCGs in Phase III of this research. The main objectives of the garment analysis were therefore:

1. To re-engineer the SCGs and obtain relevant garment design specifications.
2. To obtain pressure values applied to mannequins.

The data required achieving these objectives included details about the technical garment design (flat measurements, pattern, grading) and construction, as well as PMs. The protocol for the garment analysis was defined as follows:

1. Take flat measurements of all garments.
2. Document garment design.
3. Analyse construction of garments.
4. Create garment patterns.
5. Identify grading principles applied.
6. Measure pressure on mannequin.

1. Take flat measurements of all garments

Before taking flat measurements of the SCGs, it had to be decided what measurements were to be taken. Industry specification sheets and literature (Brackenbury, 1992; Myers-McDevitt, 2009; Bubonia, 2014) were used to consult this decision. Recommended garment measurements for knitted tops and bottoms were selected from these sources with a specific focus on width measurements, as they were of particular interest in relation to pressure application. Additional measurements were added to suit the specifics of the garments. The selected garment flat measurements for this study are listed in Appendix M with corresponding technical drawings.

The SCGs were measured in sizes Small, Medium and Large lying flat on a table following the measurement instructions by Myer-McDevitt (2009). It was attempted to lay the garments as flat as possible and any major folds were flattened out. However, care was taken not to handle the garments too much, as handling and placing knitted garments on a flat surface can induce stretch of up to 5% (Brackenbury, 1992). Circumference measurements were measured as half measurements. A tape measure (hoechstmass®, Hoechstmass Balzer GmbH, Sulzbach, Germany) and a metal ruler (Facom, Stanley Black & Decker France SAS, Morangis Cedex, France) were used to take measurements. The tape measure was calibrated using the metal ruler prior to taking the measurements.

The recorded garment measurements were compared across sizes and grade increments were identified for each measurement location. These values were later used to grade the garment patterns.

2. Document garment design

In order to have a permanent documentation of the garment design, the SCGs were photographically recorded in flat condition and whilst dressed on a mannequin using a digital SLR camera (Canon EOS 700D, Canon Inc., Tokyo, Japan). The Medium-sized garments was fitted to a size 12 Alvanon soft series mannequin (AlvaForm, Alvanon UK Ltd., London, UK) and photographs were taken from different angles. Further, technical drawings were created in Abobe Illustrator CS6 (Adobe Systems Incorporated, San Jose, CA, USA).

3. Analyse construction of garments

The construction of the SCGs was analysed and joining methods, stitch and seam types were recorded. Relevant standards (British Standards Institution, 1991a, 1991b) were used to describe stitches and seams where possible. The seam positioning and fabric placement were recorded in technical drawings of the garments. Reasons for the use of specific seam and stitch types and placement were considered in relation to body physiology and movement.

4. Create garment patterns

The patterns of the SCGs were re-engineered by unpicking the seams of one compression top and one pair of tights in size Medium. The individual fabric panels were then copied onto pattern paper. The paper patterns were cut out and annotated before being digitised using a GERBERdigitizer™ (Gerber Technology, Tolland, CT, USA). The size and shape of the pattern pieces were then opened in the pattern design software AccuMark® (Gerber Technology) and model files were created for the compression top and tights. The pattern pieces were checked against the real garments and minor amendments were conducted where necessary to clean the pattern pieces. Annotations were added where required.

5. Identify grading principles applied

The digitised patterns were graded down to size Small and up to size Large using the grades calculated from the garment flat measurements in the pattern design software AccuMark® (Gerber Technology). Pattern grading literature (Cooklin, 1990; Shoben and Taylor, 2004; Mullet, 2015) informed this process.

The applied grade increments were compared to general industry grade rules and it was determined at what parts of the body the highest grade increments were applied.

6. Measure pressure on mannequin

Before WTs were conducted to assess the fit and compression of the Skins A400 Women's Active Long Sleeve Top and Women's Active Long Tights, the pressure applied by the SCGs was measured on mannequins. The aim was to get an initial idea of the pressure levels and pressure distribution of the garments and to measure compression under different testing conditions. For this purpose, two AlvaForm soft series mannequins (Alvanon UK Ltd.) in size 12 were dressed with the SCGs. Mannequins from the Alvanon soft series were selected for this study, as their memory foam body with internal skeleton exhibits similar properties to human tissue in contrast to conventional fibreglass mannequins (Alvanon, 2013). The body dimensions of the mannequins are listed in Table 4.4.

Table 4.4: Body dimensions of AlvaForm mannequin in size 12

Body circumference measurement (cm)	Size 12
Chest	90
Small of waist	72
Hip	98
Biceps	28.5
Forearm	23.5
Wrist	16.5
Thigh	57
Knee	36.5
Calf	36
Ankle	25

Pressures applied by the SCGs were determined using the pneumatic PM device PicoPress® (Microlab, Padova, Italy). PicoPress® has previously been used to quantify compression and has been found to provide accurate and reliable results (Partsch and Mosti, 2010). The PicoPress® sensor (dia. 50mm) was placed flat between the mannequin's surface and the SCG at each respective predetermined measurement location. The fabric was flat over the sensor with no folds. The PM device displayed values to the nearest 1mmHg. Pressure values were measured three times at each PM location and the mean was used for data analysis.

22 PM locations across the upper and lower body were selected for the main PM study, as shown in Appendix N. The measurement locations were identified based on body and garment landmarks. More information about the selection of measurement locations can be found in the subsequent section (4.4.3.3).

Pilot Study

The purpose of the pilot study was threefold. Firstly, it acted as a verification of the realiblity of the PM process by repeating the PMs using two different mannequins of identical body dimensions and composition at two different occasions. This would also allow insights into potential effects of environmental factors on pressure levels.

Secondly, it assessed fabric relaxation, which has been reported to affect pressure levels (Chen et al., 2013). Pressure levels applied by the SCGs were recorded shortly after the garments were put onto the mannequin and 24 hours later. Differences in pressure levels were analysed using a Wilcoxon signed rank test.

Thirdly, it served as an assessment of the effects of seams on pressure levels. Existing research (Allsop, 2012) has reported substantial drops in pressure levels under seams using a Tekscan PM device. The SCGs under investigation featured a large number of seams. During the subsequent WTs, the SCGs would be worn by women of varying body shapes resulting in potentially varying seam positioning across body landmarks. As a result, it was important to examine the pressure behaviour under and around seams. These findings would be helpful in the determination of appropriate PM locations for the WTs. Table 4.5 lists the PM locations included in the assessment of pressure behaviour under seams.

Table 4.5: Selected PM locations to assess pressure behaviour under seams

<table>
<tr><th>SCGs</th><th></th><th>PM location</th><th></th></tr>
<tr><td rowspan="2">Top M</td><td rowspan="2">Shoulder</td><td>S-US</td><td>Under shoulder seam</td></tr>
<tr><td>S-NS</td><td>Next to shoulder seam</td></tr>
<tr><td rowspan="4">Tights S</td><td rowspan="2">Calf</td><td>C-US</td><td>Under lower calf seam</td></tr>
<tr><td>C-NS</td><td>Next to lower calf seam</td></tr>
<tr><td rowspan="2">Knee</td><td>K-US</td><td>Under seam at topend of knee panel</td></tr>
<tr><td>K-NS</td><td>Next to seam at topend of knee panel</td></tr>
</table>

Pressure Measurements in Different Test Conditions

As a large range of body dimensions have to fit into each size category, it was of interest to explore the effects of size variations on pressure application for the SCGs under investigation. Some researchers (e.g. Dascombe et al., 2011; MacRae et al., 2012) have explored pressure levels applied by undersized, adequately sized and/or oversized SCGs. This approach was also followed by this study.

It has also been stated that moisture content in fabrics could affect pressure delivery (Macintyre et al., 2016). However, there were no existing studies quantifying pressures in dry and wet garment conditions. Consequently, PMs on a mannequin were taken in wet condition by spraying the inside of the garments with water using a conventional spray bottle.

The different measurement conditions listed in Table 4.6 had the purpose of providing an indication of how different sizes and moisture content of fabrics influence pressure behaviour, which could have important implications for the design of SCGs.

Table 4.6: Different measurement conditions for pressure measurements on a mannequin

<table>
<tr><th></th><th>Test Condition</th><th>Garment size</th><th>Mannequin</th></tr>
<tr><td>US-C</td><td>Undersized condition</td><td>Top: Small
Tights: Small</td><td rowspan="4">AlvaForm soft series size 12</td></tr>
<tr><td>AS-C</td><td>Adequately sized condition</td><td>Top: Medium
Tights: Medium</td></tr>
<tr><td>OS-C</td><td>Oversized condition</td><td>Top: Large
Tights: Large</td></tr>
<tr><td>W-C</td><td>Wet condition</td><td>Top: Medium
Tights: Small</td></tr>
</table>

Comparison of Pressure Data to Different SCGs

In order to have a point of comparison of pressure levels applied by similar commercial women's SCGs, one long sleeve compression top and long compression tights in size Medium from the compression sportswear brand Sub Sports (Thirsk, North Yorkshire, UK) were acquired. Sub Sports sell SCGs at a medium price point. The exact SCGs used were Elite RX Women's Long Sleeve Compression Top and Elite RX Women's Compression Leggings (refer Appendix O). The pressures applied by the Sub Sports garments were measured at the pre-determined 22 locations across mannequin A. The pressure levels and distribution across the body were compared to the Skins PMs.

Post-Wearer Trial Garment Analysis

At a later stage, after the SCG WTs had been conducted, the SCGs were again scrutinised to assess the effects of wear and care on the garments and particularly on compression levels. At this point the SCGs had been worn by participants of varying shapes in the 33 WTs. However, due to an uneven size distribution across participants, the wear frequencies varied widely across the individual garments. The compression tights in size Small (n = 22) and the compression top in size Medium (n = 18) had been worn most often. The focus was, therefore, on these garments. At first, the garments were visually assessed for signs of wear, which were photographically recorded. The garment flat measurements were repeated to assess whether they had changed after repeated wear.

The compression top in size Medium and the compression tights in size Small were then washed at 30 degrees using a 55-minute sportswear wash programme of a domestic Type A washing machine (Maxx 6 VarioPerfect, Bosch, Germany) in a laboratory environment. It was chosen to use a domestic washing machine to replicate the usual care process SCG users would apply. As recommended by BS EN ISO 6330-2012 (British Standards Institution, 2012), 20g of ECE (European Colorfastness Establishment) reference detergent without optical brightener was used. The garments were line dried after the wash. Once fully dry, the SCGs were re-measured and measurements were compared to the pre- and post-WT garment flat measurements. Another 4 washing and drying cycles were performed using the described process. The applied pressure levels were also re-measured on the mannequin after the WTs, and after the first and the fifth washing and drying cycle. The applied washing test protocol is summarised in Figure 4.10. Table 4.7 lists the different measurement conditions for the garment flat measurements and PMs.

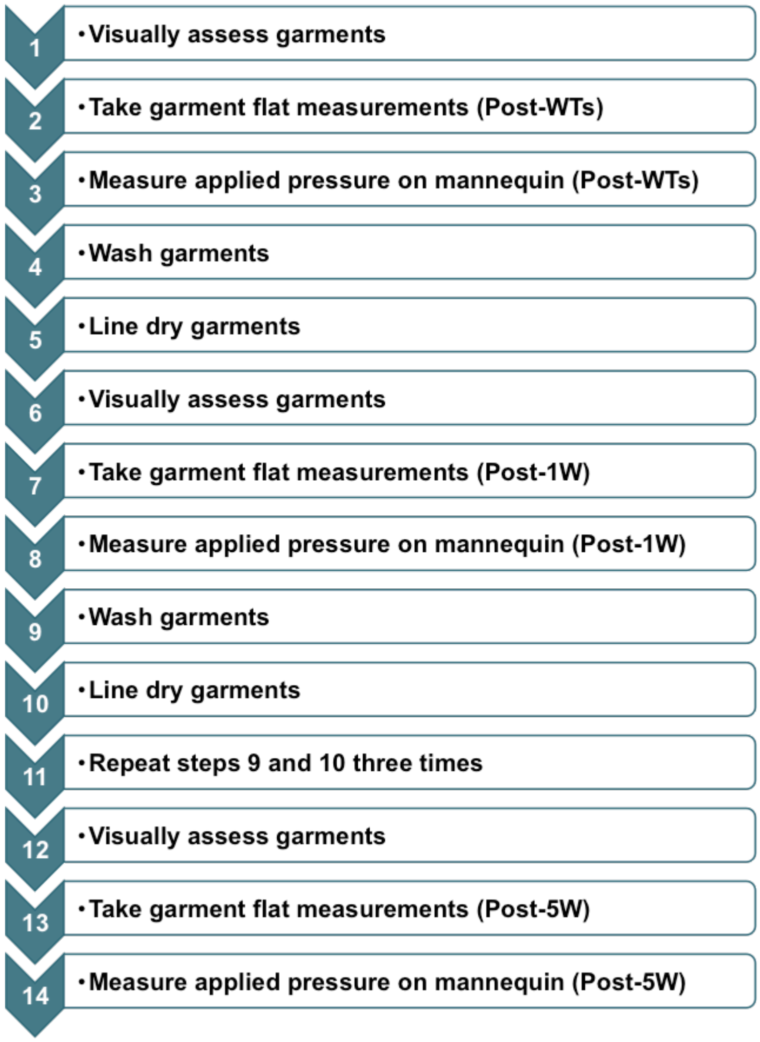


Figure 4.9: Wash test protocol

Table 4.7: Different measurement conditions for garment flat measurements and PMs

Test condition	
Pre-WTs	Before SCGs were worn in WTs
Post-WTs	After SCGs were worn in WTs
Post-1W	After 1 wash and dry cycle
Post-5W	After 5 wash and dry cycles

Framework for Data Analysis

The pressure data were compared and differences in measurements were calculated. Non-parametric tests were used to identify differences in pressure levels and garment flat measurements in the different measurement conditions as outlined in Table 4.8 and 4.9, respectively.

Table 4.8: Statistical tests used to analyse pressure data

<table>
<tr><th>Test condition</th><th>Statistical tests</th></tr>
<tr><td>US-C</td><td rowspan="3">Friedman tests and post-hoc Wilcoxon signed-rank tests with Bonferroni correction to examine whether there were significant differences between PMs of the different sizes</td></tr>
<tr><td>AS-C</td></tr>
<tr><td>OS-C</td></tr>
<tr><td>W-C</td><td>Wilcoxon signed-rank tests to examine whether there were significant differences between PMs of the dry (AS-C) and wet condition</td></tr>
<tr><td>Pre-WTs</td><td rowspan="4">Friedman tests and post-hoc Wilcoxon signed-rank tests with Bonferroni correction to examine whether there were significant differences between PMs at the different PM occasions</td></tr>
<tr><td>Post-WTs</td></tr>
<tr><td>Post-WTs</td></tr>
<tr><td>Post-5W</td></tr>
</table>

Table 4.9: Statistical tests used to analyse garment flat measurements

<table>
<tr><th>Test condition</th><th>Statistical tests</th></tr>
<tr><td>Pre-WTs</td><td rowspan="4">Friedman tests and post-hoc Wilcoxon signed-rank tests with Bonferroni correction to examine whether there were significant differences between PMs at the different PM occasions</td></tr>
<tr><td>Post-WTs</td></tr>
<tr><td>Post-1W</td></tr>
<tr><td>Post-5W</td></tr>
</table>

The resulting data from the analysis of the Skins SCGs were garment specification sheets and Bills of Materials for the compression top and tights containing technical design information as well as the digitised, graded patterns. These data were needed for the garment simulation in Phase III. Additionally, pressure data measured on mannequins were an output of the garment analysis process. These data were later used to compare pressures measured on participants in the WTs.

Size Chart Review

SCGs differ from conventional sportswear, as they are designed to apply a defined level of pressure to the wearer’s body. Inevitably, fit and sizing of SCGs are even more critical than in conventional sportswear. This warrants a review of existing size charts for commercial SCGs. The review of relevant literature in the field of sizing and fit informed the size chart review and the objectives were defined as follows:

1. To identify sizing methodologies used by SCG brands.
2. To compare sizing systems used by different brands.
3. To assess the suitability of different sizing systems for the WT participants.

In order to achieve these objectives, not only the size charts applied for the Skins SCGs under investigation, but also size charts from other commercial SCG brands had to be analysed. Once the size charts were identified, the underlying sizing methodology was analysed and the different size charts were compared to size charts used in conventional sportswear and the Skins A400 size charts. According to Skins (2016), the size charts for the A400 SCGs are based on 400 key fitting points that were established from 3D body scans of hundreds of recreational and professional athletes. The Skins A400 size charts were, therefore, seen as a good exemplar to compare other size charts to.

The procedure for analysing the size charts was loosely based on the method of document analysis, which is an unobtrusive analysis process with high reliability (Robson and McCartan, 2016). However, it was adapted to meet the specific needs of this study. The different steps of the size chart review procedure are listed below:

1. Formulate research questions.
2. Identify size charts for review.
3. Analyse identified size charts.
4. Compare and contrast different size charts.
5. Summarise the results of the size chart review.

1. Formulate research questions

The following research questions were formulated based on the objectives of the size chart review:

- What sizing methodologies are the size charts based on?
- What ranges of body measurements are included in the size charts?
- How do size charts for SCGs compare to size charts for conventional sportswear?
- How do size charts from different SCG brands compare?

2. Identify size charts for review

All SCG brands that were listed in question 11 of the online survey (‘What brand(s) of compression garments do you usually wear?’) including all brands (*N* = 45) mentioned by survey respondents were considered for inclusion in the size chart review. However, in order to allow for the research questions to be answered, two inclusion criteria had to be fulfilled:

- The brand needed to have a separate size chart for compression sportswear.
- The brand’s size chart for SCGs needed to be publicly available on the brand’s website.

This left eleven size charts for review in addition to the Skins A400 size charts. Due to the inclusion criteria, all size charts covered in the review were from specialist compression sportswear brands. The included brands are listed in Table 4.10.

Table 4.10: Compression sportswear brands included in the size chart review

SCG Brand	Company
Skins	SKINS International Trading AG, Steinhausen, Switzerland
2XU	2XU, Pty. Ltd., Hawthorn, VIC, Australia
Body Science	Body Science International, Burley, QLD, Australia
CEP	medi GmbH & Co. KG, Bayreuth, Germany
Compressport	Compressport International, Nyon, Switzerland
CW-X	Wacoal Sports Science Corporation, New York, NY, USA
Enerskin	Enerskin America, New York, NY, USA
IntelliSkin	IntetelliSkin, Newport Beach, CA, USA
LineBreak	Swooping Jack Sports International, Melbourne, Australia
Sub Sports	Sub Sports, Thirsk, North Yorkshire, UK
Virus	VIRUS Action Sports Performance UK, Bacup, Lancashire, UK
X-Bionic	X-Technology Swiss R&D AG, Wollerau, Switzerland

3. Analyse identified size charts

Size charts for the upper half and the lower half of the body are often supplied separately by brands. The same is true for most of the identified size charts for SCGs. Consequently, the size charts for compression tops and tights were analysed separately. The sizing methodologies applied were analysed by examining the size chart design, size designations, incorporated body measurements, fit range and grades of the size charts.

4. Compare and contrast different size charts

The different sizing systems applied by the SCG brands were contrasted in order to understand which body measurements were included in the size chart development. Fit ranges of the brands' applying the same sizing system were compared. Finally, the SCG size charts were compared to size charts applied in conventional sportswear.

5. Summarise the results of the size chart review

The results of the analysis and comparison of the different size charts were reported and tables were created to summarise fit ranges and included body measurements. Overlays of the Skins size chart and other comparable size charts for compression tights were created to visualise size variations between the different size charts.

Post-Wearer Trial Size Chart Assessment

Once the size charts were analysed and after the WTs had been conducted, size charts that combined weight and/or height measurements with circumference measurements were assessed for their suitability by attempting to allocate sizes to the WT participants based on the body dimensions obtained during the WTs.

Limitations of Study 2

The researcher acknowledges that the properties obtained from the fabric and garment analyses in Study 2 are not generalisable to all commercial SCGs, but are only valid for the specific SCGs used for the analyses.

The fabric analysis was limited by the amount of fabric samples that could be obtained from the SCGs. As some pattern panels were very small, it was not possible to test all fabrics in course and in wale direction and some fabrics had to be tested with fewer samples than stated in the testing standards. This was a limitation of the circumstances and could not be avoided. To ensure research integrity, the researcher has clearly expressed which tests were performed on which fabrics and stated when a smaller number of samples was used than the number specified in the applied standard.

The different process steps of re-engineering SCGs can bring about minor variations in the final re-engineered garments. The difficulties of measuring knitted garments have already been reported. Deconstructing SCGs made from elastomeric warp knits by unpicking seams can stretch and twist fabric panels, whilst copying knitted fabric panels onto paper can be difficult as edges often roll up. All these stages of re-engineering the SCGs could have induced small variations to the original SCGs. Expert advice was used to eliminate these risks as much as possible. However, despite great care taken by the researcher, some grade increments calculated from the garment flat measurements, were slightly irregular across the body. Based on guidance from a pattern grading expert, these values were averaged in order to grade the garments appropriately without changing the design or fit of the garments. These changes were only as small as millimetres and are not likely to affect the garments, but it has to be considered that, whilst the re-engineered garment patterns are a very close representation of the original SCGs, small variations can be present. To some extend this was unavoidable, as the grading method applied by Skins was unknown and sized garments might vary slightly depending on where on the garment grades are added. However, due to the high level of elastane in the SCGs, it is unlikely that these changes would be noticeable.

It has to be considered that the size charts obtained for the size chart review were taken from the brands' websites without examining the brands' garments and thus no indications can be made on how accurate the size charts are. However, since these size charts were published online to guide customers' size selection, it can be assumed that the sizing information provided was correct.

In order to increase the validity of the results, the fabric and garment analyses and size chart review followed strict methods and applied industry standards and established instruments where possible. By only having one researcher taking all measurements, potential measurement bias was reduced. The reliability of the research was further supported by the transparency of the methods and data collection techniques described in this section.

4.4.3.3 Study 3: Sports Compression Garments and the Human Body

The focus of Study 3 lay on the relationship between SCGs and the human body. WTs were believed to be the best method to develop a better understanding of the body-garment-relationship, as they are an established method to evaluate garments on the users' body with close control over participants (British Standards Institution, 1994). As WTs with SCGs focusing on pressure, fit and perception were a novel approach, there were no established protocols that could be followed for data collection. However, researchers had investigated different aspects of the SCG-body relationship (e.g. sports scientists measuring pressure, clothing researchers using 3D body scanners) and, therefore, methods could be derived from these studies. The objectives of the WTs were defined as follows:

1. To analyse the body dimensions of the WT participants and obtain body avatars that can be used for virtual fit.
2. To evaluate how the SCGs under investigation fit the WT participants' bodies.
3. To explore the WT participants' perceptions and evaluation of the SCGs in terms of design, fit, comfort and compression.
4. To quantify pressures applied by the SCGs to the WT participants' bodies.
5. To identify whether there are any relationships between body dimensions, pressure levels and fit that could support the prediction of pressures applied by SCGs.

Wearer Trial Design

In order to fulfil the above objectives, four different types of data needed to be collected in the WTs: body measurements (objective 1), photographs to document garment fit (objective 2), perceptual data (objective 3), and pressure data (objective 4). The multitude of data required various methods and technologies to be applied in the WTs. The WT procedure was divided into four key stages to obtain these data: 1) capturing 3D body scans of participants with and without SCGs, 2) photographically recording the WT participants' bodies wearing the SCGs, 3) collecting perceptual data through a short questionnaire, and 4) quantifying compression using a PM device. The Skins A400 SCGs analysed in Study 2 were used for the WTs.

The WT step-by-step experimental protocol is shown in Appendix P. During the WTs a technician was present at all times. Both the researcher and the technician maintained a professional manner to put the participants at ease and to ensure objectivity of the WTs. After introductions and a briefing of the WT procedure, the participants signed the consent form. The participants' body measurements were captured using a 3D body scanner. Participants were asked to wear the type of sports bra they would usually wear during exercise to reproduce the natural fit of a use situation. Following the body scan in underwear, each participant wore Skins A400 Women's Active Long Tights and a Skins A400 Women's Long Sleeve Top in size S, M or L. Sizing was determined by the ratio of height and weight for the tights and the chest circumference for the top using the brand's size chart. Photographs were taken to visually record the fit of the garments. The participants were scanned again whilst wearing the SCGs, however, before the scan was captured, 22 locations across the body were marked on the outside of the SCGs using tape. The body scan with SCGs was captured in colour, so that the tape marks would be visible when analysing the data. After the second scan, a wearer feedback questionnaire investigating opinions and perceptions of the SCGs was conducted. Finally, pressures applied by the SCGs were measured at the previously marked locations using a pneumatic PM device. At the end of the WT, participants were given a printout of their body measurements along with an image of their 3D refined body mesh (RBM), i.e. the body avatar output of the 3D body scanner.

The measured compression values and body scan avatars were required for Phase III of the study to assess the validity of 3D CAD pressure maps.

Pilot Study

A pilot study was conducted with one participant to assess whether the WT procedure was feasible, to measure the required time for each step of the WT, and to do a dry run of the data analysis. The pilot study followed the WT protocol outlined in Appendix Figure P-1. The participant was a 24-year-old active female who regularly exercised 5 hours a week. She volunteered to take part in the pilot study and gave informed consent. The researcher, the technician and an observer were all present throughout the trial. The order of the WT process worked well and there were no problems with the applied technologies or methods. The only changes made after the pilot study were changes to the order of the PMs on the recording sheet to maximise measurement efficiency by having a more logical measurement flow. It was aimed to keep the WTs to a maximum of one-hour in length to increase the chances of recruiting volunteers to take part in the study. The pilot study took just under 60 minutes. It was believed that the more logical flow in pressure measuring and familiarity with the procedure would lead to a reduction of this time. The participant, technician and observer were asked for feedback and everyone was confident that the WT procedure worked well and did not require any further changes.

Sampling

The inclusion criteria for the sample were that participants had to be female between the ages of 20 and 55 years who exercised a minimum of 5 hours a week. Initially the age range was set at 20 to 40 years, however, due to early problems with sampling recruitment, the age range was raised to 55 years.

The WT study applied a non-random volunteer sampling technique. Whilst random sampling is the ‘gold standard’ in sampling methodologies (Williamson, 2003), it was not possible in this case, as the sampling frame was unknown and the involvement of participants was based on their willingness to volunteer as there was no financial incentive to partake in the study. It is common practice to use non-random volunteer sampling techniques in clinical research and sports studies (Lunsford and Lunsford, 1995; Atkinson, 2012). The researcher tried to minimise bias of this non-random sampling technique by applying a consecutive sampling approach. This meant that every available subject matching the inclusion criteria was selected for the study. This approach results in good representation of the overall population because the complete accessible population is studied (Lunsford and Lunsford, 1995). As is true for many experimental studies involving volunteers (Atkinson, 2012), the sample evolved over time as WTs were conducted.

Participants were recruited through posters with research information and contact details (see Appendix Figure P-2) distributed across the university campus and in local fitness centres. Emails were sent to all online survey respondents who expressed interest in participating in the WTs as well as to the MMU Sport marketing officer asking her to share the information within her network. The recruitment poster was also shared online in selected forums and social media groups.

The sampling strategy was supported by snowball sampling as participants were asked to share the information about the study within their networks. With the main focus on quantitative correlations between body measurements and garment pressure, this sampling technique was regarded as appropriate for the study.

A standard process was devised for the recruitment of volunteers from the point of initial contact. Interested individuals approached the researcher via email. The researcher then sent the WT information sheet (see Appendix Figure P-3) to the potential participant. The information sheet included details about the rationale of the WTs, the procedure, potential risks, and data confidentiality. It aimed to answer all anticipated questions. The potential participant was encouraged to ask any additional questions. The WT information sheet stated that if the individual was interested in participating in the study, she should respond to the researcher's email. If the individual did not respond after sending the WT information sheet, it was assumed that the individual was not interested in participating in the study. Once a response was received, a link to an online scheduling poll showing available appointment times was sent to the participant to select the most suitable time and date for the WT. A standard confirmation email was sent to the participant indicating the date, time and location of the WT. A phone number was provided for the case that the participant needed assistance in finding the meeting point or was running late.

WTs are generally small-scale studies that can yield useful data from just 10 to 12 participants (British Standards Institution, 1994). A similar sample size is usually applied in sports studies. The average sample size of the 146 identified studies on the functionality of SCGs in Chapter 2 was 15. Based on these numbers, it was initially aimed to target a sample of 12 to 18 participants. The WT data collection was conducted in two parts. The first part was carried out from mid-June to the end of August 2016 at the School of Materials at the University of Manchester (UoM) due to a malfunction of the body scanner at the Manchester Fashion Institute (MFI) at Manchester Metropolitan University. After initial recruitment problems, the use of snowball sampling proved to be a successful strategy, so that

21 WTs were conducted over this 2.5-month-period. Due to technical issues not all data could be collected for one of the participants, who was subsequently excluded from the analysis. When the data of the 20 remaining participants were analysed, it became apparent that there were no participants wearing Large-sized compression tights. The sampling strategy did not allow for the selection of volunteer participants and, therefore, the range of sizes was arbitrary. Whilst it was acknowledged that the BMI-based size chart for the compression tights was very generous, as participants mostly wore one size smaller in the compression tights compared to the compression top, it was also suspected that there was an element of bias towards slimmer participants in the sample. A possible reason for this, apart from the fact that women exercising a minimum of 5 hours a week generally tend to be slimmer, was that women of a larger body size were potentially less likely to volunteer to be scanned, as their body confidence might be lower than in slimmer women. It was originally attempted to eliminate this potential bias by depicting a range of different women and body shapes on the WT recruitment poster. At this point, it was unclear whether there was a bias in the sample or whether the Skins size chart for tights was simply very 'generous'. It was, therefore, decided to conduct further WTs with the aim to recruit participants that would fit into the Large-sized compression tights. New recruitment flyers were designed stating that the researcher was particularly interested in active women weighing 7 stones (76kg) or more (see Appendix Figure P-4). The flyer depicted a picture of a slightly larger runner to visually support the message. The weekly hours of exercise were also relaxed to 3 hours from 5 hours per week. The second part of the WT data collection took part from mid-January to mid-May 2017 at the MFI, where 13 WTs were conducted. The WT protocol, the 3D body scanner and the ethical protocols were identical to the first part of the WTs.

In total 33 female participants were included in the analysis of the WTs. A sample size above 30 is a sufficient number for non-experimental designs involving relations in a single group and permits the use of statistical correlation analysis (Cohen, 1992; Robson and McCartan, 2016).

Consent and Data Protection

On arrival, participants were welcomed by the researcher and shown to the body scan laboratory, where the WT took place. They were introduced to the technician supporting the trials and given a description of the WT procedures. They were given the opportunity to read the WT information sheet again and to ask any questions. Participants then signed the consent form, which clearly stated participants' rights (see Appendix Figure P-5), and the participant's identity was coded, so that all data collected during the trial was recorded using only the identification code as reference to ensure confidentiality of the participant. The participant was asked to enter some demographic information, including age, gender and ethnicity into the departmental body scan database and sign an additional consent form for the body scanning part of the study. This was a requirement of the UoM and MFI's body scan procedure. The signed consent forms, linking the participants' names to the identification codes, where stored in a secure location.

3D Body Scanning

Over the past two decades, 3D body scanning technology has evolved vastly and is now an established method of capturing accurate anthropometric body data. The advantages of 3D body scanning have been discussed in the literature review (refer section 3.3.2). A 3D body scanner was chosen as a tool for this study, as it is an efficient way to capture participants' accurate body measurements, allows a detailed analysis of the data and produces avatars of the participants' bodies that were required for Phase III of this research project.

Instrumentation

The 3D body scanner used for this study was a full-body, non-contact Size Stream SS14 (Size Stream, Cary, NC, USA) surface scanner. The scanner uses infrared depth sensor technology to generate a 3D digital image of the body being scanned, similar to the technology used by Xbox Kinect game consoles (Microsoft, USA). The body is captured within 6 seconds by 14 sensors that are located at the front and the back of the body at seven different heights and six different angles. In order to extract measurements from the raw sensor data, the scanner converts the raw data into a RBM. The data processing time after the scan takes up to 30 seconds. The scanner's accuracy in circumferential measurements is reported as <±5mm (Size Stream, 2016). The scanner is able to capture colour scans, however colour data is only visible in the raw scan data, not in the RBM. The body silhouette generated from the scan data and the extracted measurements are visualised in the scanner's accompanying scan software (Size Stream Studio). The scan can be reviewed and further analysed using the software.

The following additional equipment was required for the body scanning part of study 3:

- Ergonomic circumference measuring tape (Seca, Hamburg, Germany), 1mm scale, calibrated against a metal ruler;
- Stadiometer (Seca), 1mm scale;
- Flat scale with cabled remote display (Seca), 0.01kg scale, rounded to 0.1kg;
- Dressing gown, to be worn at all times when unclothed, except when in scan or changing cubicle;
- Hair ties and clips, to ensure that neck and shoulder measurements were not obstructed by hair;
- Microporous tape, to mark PM locations on outside of SCGs.

In order to verify the body scan accuracy, a small-scale validation study with one participant was conducted. The participant's body dimensions were measured manually and by using the 3D body scanner both whilst wearing whole-body compression sportswear as outlined in Appendix Q.

The Measurement Display List determines which measurements are extracted from the scan file. The list can be customised in the Size Stream Studio software. The required measurements for this study were selected based on a review of literature and previously reported measurements and belonged to two groups: measurements related to fit and pattern construction and measurements related to the PM locations, which were based on the anatomy of movement and muscles and garment design characteristics. A list of measurements selected for this study with relevant standards can be found in Appendix R.

It is only possible to extract body measurements from the scan data captured with the Size Stream SS14 body scanner, when the body is in the standard scan posture. An attempt by the researcher to extract body measurements from a mannequin that was not in the exact scan posture was unsuccessful. Whilst it was possible to obtain a refined body mesh file, which could be used as an avatar in 3D CAD, it was not possible to obtain any measurements, neither automatically nor manually, as there were no landmark points in the refined body mesh. The standard scan position for the Size Stream scanner is similar to standing position A of BS EN ISO 20685:2010 (British Standards Institution, 2010) with the participant standing erect with the head in the Frankfurt plane with feet 20cm apart and the arms abducted to form a 20-degree-angle at the upper arms and the sides of the torso (see Figure 4.11). The feet are parallel and elbows straight. However, during scanning palms are not facing backwards, but the participant is holding on to handholds located on either side of the body within the scanner cubicle. The handholds slide vertically, so that the participant can stand upright in a normal relaxed posture while holding the handholds (Size Stream, 2016).

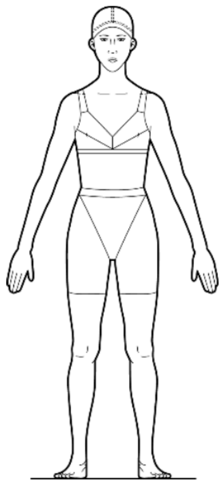


Figure 4.10: Standing position A (British Standards Institution, 2010:15)

Body scanning procedure

Established institutional standard body scan protocols were used to capture the 3D body scans of the participants. The researcher and the technician were both trained in the procedure prior to performing the 3D body scans. The different steps of the body scanning procedure are described in Appendix S.

After the body scan in underwear was taken, the participant was asked to wear the SCGs for the second scan. The size for the long sleeve top was based on the chest measurement extracted from the body scanner and the size for the tights was based on the height and weight measurements obtained prior to the body scan. The participants changed into the SCGs in the private changing cubicle, whilst the technician set the body scanner to colour scan mode. Before the second scan in SCGs was taken tape marks were added on the outside of the SCGs at 22 locations across the body. These locations were selected based on body landmarks and garment characteristics and were the locations where compression was later recorded. The intention was that these points would be visible on the scan data, so that the circumference measurements at the PM locations could be measured using the slice tool in the Size Stream Studio software. These data were required to analyse any potential correlation between the circumferences and measured pressures.

Selection of Pressure Measurement Locations

The 22 PM locations were selected based on a detailed review of literature on PM locations on medical compression stockings (MCS) (Wildin et al., 1998; British Standards Institution, 2001; Partsch, Clark, et al., 2006) and studies measuring compression on SCGs (Sear et al., 2010; MacRae et al., 2012; Brophy-Williams et al., 2015). Whilst there are no standards in measuring compression on SCGs, a European document for normalisation for the measurement locations of MCS exists (British Standards Institution, 2001). The document identifies nine measurement locations as listed in Table 4.11 (British Standards Institution, 2001; Partsch, Clark, et al., 2006).

Table 4.11: Measurement locations for medical compression stockings

Standard Descriptor	Location on Body
B	Ankle at point of minimum girth
B1	Area at which the Achilles tendon changes into the calf muscles (B10–15 cm proximal to the medial malleolus)
C	Calf at its maximum girth
D	Just below the tibial tuberosity
E	Centre of the patella and over the back of the knee
F	Between K and E (mid-thigh, between patella and groin)
G	5cm below the centre point of the crotch
H	Greatest lateral trochanteric projections of the buttock
K	Centre point of the crotch

Partsch and colleagues (2006) presented the results of a consensus group providing recommendations to lead to a more standardised procedure in reported pressures under compression devices in medical practice. The authors suggest that pressures should not be measured over bony prominences and identified B1 as the most valuable measurement location for medical compression studies because the leg circumference shows the biggest enlargement during dorsiflexion at this point. MacRae et al. (2011, 2016) later recommended the use of locations B1, C and F as a minimum standard for studies measuring pressure on sports compression tights. Not many studies have measured applied pressures of compression tops. The only researchers identifying the exact locations used for PMs of compression tops are Sear et al. (2010). The researchers used four locations across the top: at the forearm, biceps, front chest muscle and oblique muscle.

This study followed the recommendations of existing research and selected, where possible, the measurement sites based on muscles, rather than body tissue (Partsch, Clark, et al., 2006; Brophy-Williams et al., 2015). The PM locations chosen based on anatomical body landmarks are listed in Table 4.12.

Table 4.12: Selected PM locations based on anatomical body landmarks

Body landmarks for tights	Body landmarks for top
5cm above the lower border of the inner ankle	Inner forearm at widest part
Area at which the Achilles tendon changes into the calf muscles (B10–15cm proximal to the medial malleolus)	Inner biceps at widest part
Back of calf at widest point	Front chest muscle at armpit level
5 cm above the midpoint of the upper border of the patella	External oblique abdominus muscle
Mid-point of the natural crease between the thigh and hip and the upper border of the patella	5cm above navel
Gluteus maximus at greatest projection	10cm below navel
	Waist at side
	Shoulder blade
	Top of shoulder

Whilst it is important to base some PMs on body landmarks in order to be able to compare results among individuals, it was also important for this study to investigate the effect that garment characteristics have on pressure levels. Therefore, the researcher added additional measurement sites, which were based on garment markers, listed in Table 4.13.

Table 4.13: Selected PM locations based on anatomical body landmarks

Garment landmarks for tights	Garment landmarks for top
Waistband centre front	Sleeve hem on inner wrist
Hem at inner ankle	Lower hem at centre front
Thigh side 5cm below waistband	Neckline at centre front
	Neckline at shoulder

The final measurement locations selected for this study are shown in Appendix N.

The selected PM locations were marked on the outside of the SCGs worn by the participant standing in the anatomic zero position. Body landmarks were identified visually and by palpation, using a tape measure to identify exact measurement locations. Once all tape marks were added, the body scan procedure was repeated with the only difference being that the scan was captured in colour. It is recognised that there is an element of subjectivity in the identification of body landmarks, but the fact that the same researcher marked the PM locations on all participants using the same identification procedure, reduces variability and error.

Framework for Data Analysis

The data obtained from the two body scans underwent a number of analyses. The body scan data analysis was conducted using the Size Stream Studio software, which allows automatic measuring using chosen measurement display lists, manual extraction of custom measurements, manipulation of landmarks and batch processing of scan data at any point without having to be connected to the scanner (Size Stream, 2016).

Before any body measurements extracted from the body scans were used for analysis, the body scan data was checked to ensure that all landmarks used to extract body measurements were located accurately on the body. For this purpose, each body scan file was opened in the Size Stream Studio software individually and the landmarks on the refined body meshes were reviewed. A shortcoming of the Size Stream Studio software is that the number of movable landmarks is fairly limited, for example, none of the landmarks on the legs are movable.

It became apparent fairly quickly that there was a problem with the shoulder point landmark with shoulder points being located too far inwards or outwards. Figure

4.12 shows the correct shoulder point location according to BS ISO 8559-1:2007 (British Standards Institution, 2017b). The shoulder point landmark was moved in the scan files where required using the images in Figure 4.12 as benchmark. Some scan files also required movement of the under bust point and the bust apex. To keep track of the data cleaning process, any amendments done to the body scan data were recorded in a body scan data cleaning log.

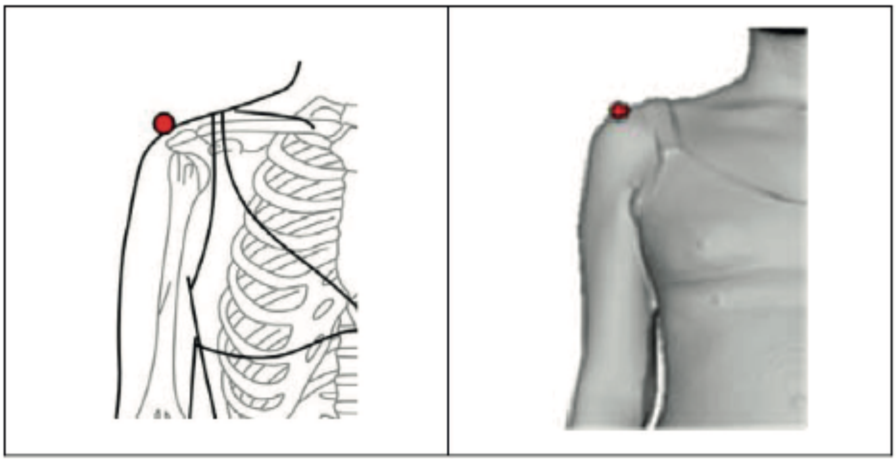


Figure 4.11: Shoulder point location (British Standards Institution, 2017b:2)

Anthropometric Analysis

Once all body scan data were reviewed and cleaned, the batch process feature in Size Stream Studio was used to extract the required body measurements from the cleaned scan data. The body measurements were analysed by calculating overall and size-specific means and ranges. Differences between body measurements with and without compression were calculated.

The anthropometric data were tested for normality using the Shapiro-Wilk test (refer Appendix T), which has been reported to be the most suitable test for small sample sizes (Field and Hole, 2003). The anthropometric data was normally distributed within the size categories with exception of right arm length for size M. Consequently, parametric tests (e.g. t-tests) were utilised for the analysis of body dimensions for the compression tights, whereas non-parametric tests (e.g. Kruskall-Wallis tests) were applied for data analysis for the compression top. Correlations were assessed using Spearman's correlation coefficient.

Body Shape Classification

As has already been discussed in section 3.3.3 of the literature review, there are many different approaches to categorise body measurements into body shapes. This study applied the methodologies suggested by Simmons et al. (2004a, 2004b), Makhanya et al. (2014), Gribbin (2014), and Rasband and Liechty (2006). Each system uses different defining parameters for the various body shape categories (refer Appendix E). Initially, the body shape classification by Simmons et al. (2004a, 2004b) was selected for this study. The Female Figure Identification Technique (FFIT) developed by Simmons and colleagues has been successfully validated (Devarajan and Istook, 2004) and widely cited, thus was believed to be a credible approach. However, an initial problem was that the FFIT requires a high hip measurement, which could not be extracted from the Size Stream scan data. Nevertheless, it was tried to categorise the participants as well as possible. 18 out of the 33 participants were eventually classed as oval shapes, even though, when visually assessing the bodies' silhouettes, they did not appear oval in shape. The body shape classification systems by Makhanya et al. (2014), Gribbin (2014), and Rasband and Liechty (2006) were also applied to the body measurement data and eventually a combination of the three systems was used. Participants classed in the same body shape category by at least two systems were classed as that particular body shape, whilst the rest of the body shapes were visually assessed to make a decision on which of the identified body shape categories was a better fit. Once all participants were classified into body shapes, Mann-Whitney tests were applied to test whether there were any significant differences in body measurements and demographic factors between the identified body shape categories.

Extraction of Slices to Obtain Circumference Measurements at Pressure Measurement Locations

A key feature of Size Stream Studio is the ability to take manual measurements from the 3D data. This gives the user the ability to gather anthropometric data that may not be available through the automatic measuring options. This feature was used to extract circumference measurements at the PM locations that were marked with a tape mark during the second body scan. In order to do this, the raw data file of the body scan had to be placed over the RBM in the software (see

Figure 4.13). This was necessary because it is not possible to extract measurements from the raw point cloud, whilst the colour data is not available in the RBM. Once the horizontal slices were extracted, overall and size-specific means and ranges of the circumferences at each PM location were calculated.

Figure 4.12: Overlay of raw colour scan data on refined body mesh (screenshot)

Garment Stretch Percentage

The garment stretch percentage was identified by calculating the difference between the garment circumference (2x width) and the body circumference measurements at key measurement locations as shown in Table 4.14.

Table 4.14: Body and garment measurements used for garment stretch analysis

		Body measurement	Garment measurement
Tights	Waist	Waist circumference	Waistband width front (measured straight at top edge)
	Hip	Hip circumference	Hip width (10cm down from top edge)
	Mid-thigh	Mid-thigh circumference right	Thigh width (5cm down from crotch)
	Knee	Knee circumference right	Knee width (½ of inseam length)
	Calf	Calf circumference right	Calf width (25cm up from bottom hem)
	Ankle	Ankle circumference right	Leg opening width (measured straight)
	Chest	Chest circumference	Chest width (2.5cm down from underarm)
Top	Waist	Waist circumference	Waist width (40cm down from shoulder high point)

	Body measurement	Garment measurement
Hip	Hip circumference	Bottom opening width (edge to edge, straight)
Biceps	Biceps circumference right	Sleeve width (2.5cm below armhole, parallel to sleeve opening)
Forearm	Forearm circumference right	Elbow width (1/2 of underarm sleeve length)
Wrist	Wrist circumference right	Sleeve opening width

Fit Assessment

Photographs with a point-and-shoot camera (Nikon Coolpix S9400, Nikon Corporation, Japan) were taken of participants wearing the SCGs to have a permanent record of the garment fit on each participant's body. Participants were asked to stand straight with weight evenly distributed across both feet. The arms were hanging by their sides. Each participant was photographically recorded from frontal, back and both side views. The photographs only captured the participants' bodies up to the neck with the face not being visible in the pictures.

The fit of the garments was later analysed using the Skin's fit guide images shown in Figure 4.14 and Figure 4.15 as a benchmark for ideal fit and intended position of the seams and panels. The pictures were available on the Skin's website (Skins, 2016) together with instructions for donning the garment to assist consumers.

Figure 4.13: Skins fit benchmark for compression top

Figure 4.14: Skins fit benchmark for compression tights

In order to standardise the fit assessment, criteria and scores for the fit assessment had to be defined. Many subjective fit evaluation methodologies based on the review of visual representations of clothed bodies, including videos and images (Kohn and Ashdown, 1998), 3D body scans (Ashdown et al., 2004; Bye and McKinney, 2010; Song and Ashdown, 2010) and 3D computer simulations (Lee and Park, 2016), have been used over the years. All approaches were based on questionnaires or assessment scales to evaluate garment fit based on the respective visuals. Whilst the use of 3D body scans for fit analysis can be appropriate in some circumstances, the negative fit of the SCGs limits its usefulness in the context of SCGs. Additionally, it is difficult to evaluate the alignment of seams with body landmarks using 3D body scans (Bye and McKinney, 2010). Due to the complex panelling and seam positioning of the Skins SCGs, the method of evaluating photographs was more appropriate for this study.

The key factor to consider in the fit analysis of SCGs was that the fabric sits flat against the body without any obvious fabric folds and creases, so that the desired pressure is applied to the underlying body. It was further important to assess seam placement, garment length and whether the garments were constricting the body at the waistband. A list of these fit criteria, informed by literature and the specifics of the particular SCGs under examination, was created. 5-point-scales based on Song and Ashdown (2010) were selected to score the length and waistband criteria, whilst a 3-point-scale based on Lee and Park (2016) was used to score the seam positioning and fabric fold criteria. The final fit evaluation criteria and scores are presented in Appendix U.

The fit benchmark images (see Figure 4.14 and Figure 4.15) and the photographs taken during the WTs were brought up on the computer screen next to each other one participant at a time and the fit was scored following the order of the fit assessment sheet (see Appendix Figure U-1 and Appendix Figure U-2). In addition to the front and back view, the left and right side view photographs were used to assess the fit of the participants when a score was ambiguous. Participants with obvious fit issues were analysed in more detail by comparing their body measurements and body shapes to the mean measurements of other participants in the same size category. In order to get an indication of whether fit directly affects compression levels, the results of the fit assessment were later compared to the measured pressure levels by identifying participants with fit issues and comparing the measured pressure at the body part with fit problems to the overall mean pressure at the respective location. It was hoped that the fit assessment would provide insights into the suitability of the Skin's size chart for women's SCGs.

Wearer Trial Questionnaire

A questionnaire was applied during the WTs in order to obtain subjective user evaluations of the SCGs. It was further hoped to get an insight into respondents' views on SCGs in general. It was considered important to conduct the questionnaire whilst the participants were wearing the SCGs, so that they could reflect on how they felt wearing the garment on the spot, rather than recalling this knowledge from memory. Recalling perceptions and emotions from memory is likely to cause inaccuracies in responses as has been shown by existing research (Thomas and Diener, 1990; Schwarz and Sudman, 1994). In order to give participants the opportunity to reflect on the questions, it was decided that rather than a self-reported questionnaire, a face-to-face survey would be a better option to conduct the questionnaire. The researcher acted as the interviewer to enable the researcher to pick up on any reactions and additional comments about the SCGs from the participants.

An extensive amount of literature on the development and administration of questionnaires had already been reviewed for the development of the online survey in Study 1. No suitable existing surveys were found to apply in Study 1, however, the context in which this questionnaire was employed, was different, as responses were collected on the spot by the researcher in an experimental situation. It is established practice to use questionnaires in experimental situations in sports studies for the assessment of athletes' feelings pre-, during and/or post-exercise tasks (Hardy and Rajeski, 1989). A small number of researchers have employed perceptual measurements related to wearing SCGs in their studies on the functionality of SCGs. Ali et al. (2007) used an 11-point-scale to assess the comfort and feel of compression stockings before and after a bout of exercise, whilst Hooper et al. (2015) used a questionnaire based on 5-point Likert scales to assess participants' comfort, perception of how much the garment was performance-enhancing and how enjoyable it was to wear the compression top under investigation. They also included a question about the perceived level of compression. Brophy-Williams et al. (2017) included a question about the perception of the efficacy of SCGs. These studies were used as a guide when developing questions for the WT questionnaire.

Questions were generated around the concepts of comfort, aesthetics, fit and perception of SCGs. A list of the generated questions can be found in Appendix V. In order to keep the WT process within the one-hour timeframe, which was believed to be an adequate time for a study that is reliant on volunteer participants, it was tried to keep the questionnaire as short as possible (approximately five minutes). Thus, mainly dichotomous and 5-point scales were used with a few open-ended questions to follow up closed questions in order to get a deeper understanding of the responses. The list of generated questions was qualitatively reviewed and questions that were ambiguous or found to be less important for the evaluation of the SCGs were eliminated. The final questionnaire consisted of 16 closed questions and a final question that gave the participants the opportunity to provide additional comments. Six of the 16 questions were followed by open-ended probing questions, which were only asked if a certain response was given to the preceding question to provide further details or reasons regarding a response. The final version of the questionnaire can be found in Appendix W.

Since the questionnaire contained some questions about the beliefs in SCGs, the researcher took care not to influence the participants' questionnaire responses. For this reason, the questionnaire was conducted before the PMs were taken as it was expected that participants would ask questions about the research and pressure levels during the PM process. When conducting the questionnaire, the researcher read out loud the question and response options and gave the participants time to reflect on the answer. This included moving in the garment or looking at the garment in the mirror, depending on the question. The responses were recorded manually on a coded questionnaire form and entered into an excel sheet where the responses for all participants were stored. Responses to closed questions were later imported into IBM® SPSS® Statistics (Version 24), where they were statistically analysed using descriptive statistics. Spearman's rho and Mann-Whitney tests were used to identify correlations between different responses. Responses to open ended questions were content analysed and grouped into themes. Individual responses highlighting discomfort or fit issues were examined in more detail by reviewing the participant's measured compression levels and result of the fit assessment.

Pressure Measurements

Once the participants' bodies were scanned, photographs were taken, and the questionnaire was conducted, the final stage of the WT was to measure the pressures that the SCGs applied to the participants' bodies. As highlighted in section 2.5.2, it is important to measure pressures on human bodies, rather than a mannequin, as it could provide insights into the effects of body composition and posture on pressure distribution. It also allowed the comparison of pressure data measured on mannequins and on human bodies. It was hoped that quantifying compression and analysing the relationships between body measurements, garment characteristics and compression would lead to a better understanding of these relationships.

Instrumentation

Pressures were measured using a PicoPress® (Microlab, Padova, Italy) handheld pneumatic PM device (refer section 2.5.2.2). The study applied a commercially available PM device to allow reproducibility of the research. A pneumatic sensor type was chosen over resistive or fluid-filled sensors, as pneumatic sensors are superior for the application in clothing. The flexibility of the PicoPress® sensor is ideal for the application on curved surfaces and during body movement. The PicoPress® PM device was chosen, as it is a state-of-the-art PM device that has been shown to be superior to other pneumatic PM devices (Mosti and Rossari, 2008). It is a popular device in clinical use due to its portability and ease of calibration, which were also important factors for this study. The PicoPress® system has previously been used for in vivo PMs and has been found to provide accurate and reliable results (Partsch and Mosti, 2010).

As the PM locations were already marked prior to the body scan in SCGs, there was no need for any further equipment.

Measurement Postures

Several researchers (e.g. Rimaud et al., 2010; Brophy-Williams et al., 2015) have measured compression in different body postures and found that compression varies significantly between varying body postures (e.g. standing, sitting, supine). It was, therefore, decided to record pressures not only in standing position, but also in other body postures. Sitting and supine positions were excluded, as, informed by the online survey, only a small proportion of the respondents wore SCGs during recovery. Besides, the Skins A400 SCGs were designed to be worn during exercise. The brand has recently introduced a separate range of recovery CGs. With this in mind, suitable postures had to be identified. Informed by literature about body physiology and the anatomy of the moving body, two postures were selected for the PMs on the compression tights and one posture was chosen for the PMs on the top. These postures were kept very basic, so that they were easily repeatable to increase inter- and intra-participant measurement reliability (Gill, 2009) and would feel natural to the participants without causing discomfort.

Posture 1 was the standard measurement position in which all measurements were taken. It was similar to the 3D body scanning position (refer Figure 4.11). Posture 1 reflects the anatomic zero position with slight changes to the arms. The participant stood erect with feet hip width apart and feet parallel. The weight was evenly distributed across the feet and the head was facing forwards. The arms were by the sides of the body, but unlike the anatomical position, the palms were facing inwards to the thighs. This was thought to reflect a more natural stance (Gill, 2009). Posture 1 is essential as all other positions are described from this standard posture (Calais-Germain, 1993).

For Posture 2 the participant adopted Posture 1 and lifted the right leg up in front of the body until the thigh was parallel to the floor and there was a ~90 degree flexion in the hip. The knee was also flexed to ~90 degrees. The participants could hold onto a chair backrest to support their balance.

Posture 3 was reached by standing in Posture 1 and lifting the heels and moving the weight onto the balls of the feet to reach the 'tiptoe' stance. Again, participants could hold onto a chair backrest to support their balance. The position of a 'tiptoe' stance was one of the recommended postures by Partsch et al. (2006). Postures 2 and 3 were both only used for the limb measurements on the tights to assess how muscle contractions and fabric strain affect pressure.

Posture 4 was related to movements in the shoulder. From Posture 1 the right arm was flexed to ~90 degrees at the elbow and lifted in front of the body to a ~90 degrees shoulder flexion, so that the upper arm was parallel to the floor. This posture was chosen, as it creates large dimensional changes across the back and the front with the back expanding and the front condensing. A visual depiction of the postures is provided in Appendix X.

Measurement Procedure

The PM process took about 20 minutes and at the start of the process the participants had been wearing the SCGs for about 20 minutes. To ensure that PMs were accurate, care was taken that the PicoPress® sensor was placed flat between the participant's skin and the SCG centrally under the tape mark on the garment. It was checked that the fabric was flat over the sensor with not folds. The pressure value was measured following the manufacturer's instruction. The researcher waited for the pressure value to settle before the pressure value was read from the screen and recorded. This usually only took about 3-5 seconds. The PM device displayed values to the nearest 1mmHg. Pressure values were measured twice at each PM location and the mean was used for data analysis. In Study 2, when measuring compression on mannequins, and in the pilot WT measurements were taken three times. However, it was noted that variations between the three measurements were minimal, therefore, it was decided to only measure the pressure values twice at each measurement location. This increased the efficiency of the study.

Measurements were taken at 22 locations across the body in measurement Posture 1. Five of the measurements of the tights were also measured in Postures 2 and 3 and four of the measurements of the top were also measured in Posture 4. This meant that 36 PMs were recorded per participant. The nomenclature for the pressure data was based on the code for the PM location plus the number for the PM position (e.g. B31).

To keep methods consistent, the PMs were taken on the right side of the participants' bodies following the strict measuring protocol outlined in Figure 4.16.

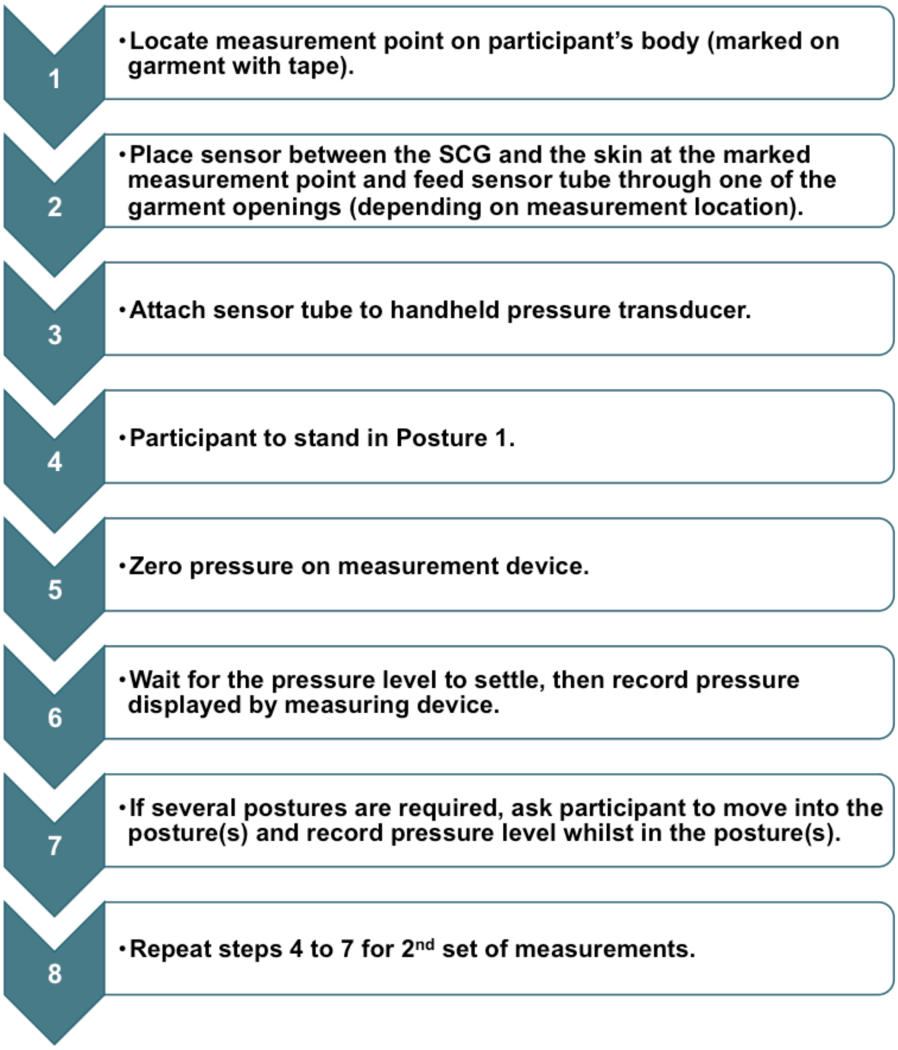


Figure 4.15: Protocol for taking PM

Pressure Data Analysis

After the WTs, the mean pressure values were entered into an excel sheet where pressure data was stored for all participants. The data were later imported into IBM® SPSS® Statistics (Version 24).

The overall and size-specific means and ranges were calculated to determine applied pressure levels and to identify variations in pressure. The pressure results were further analysed within the context of previous results, such as the participants' body measurements, garment flat measurements and pressures measured on mannequins.

The pressure data were tested for normality using the Shapiro-Wilk test, as it is the most suitable test for small sample sizes (Field and Hole, 2003). Eleven of the pressure variables conformed to normality, whilst eight did not (refer Appendix Y). As a consequence, non-parametric statistical tests were used to analyse the data. Kruskal-Wallis and Mann-Whitney tests were applied to test for differences in pressure values across different sizes and between pressures measured on mannequins and humans. Differences between pressures measured in the different measurement postures were analysed using Wilcoxon signed rank tests. Correlations between pressure values and body circumferences as well as body shapes were analysed using Spearman's rho. The following guidelines were applied to interpret the strength of effect size r and correlation coeffient rho:

- Effect size *r* (following Cohen's (1992) classification):
  - r = 0.10 – 0.29 - small effect,
  - r = 0.30 – 0.49 - medium effect,
  - r = 0.50 – 1.0 - large effect.
- Correlation coefficient rho:
  - ρ = 0.00 - 0.50 - negligible correlation,
  - ρ = 0.50-0.7 - moderate correlation,
  - ρ = 0.70-0.90 - strong correlation,
  - ρ = 0.90-1.0 - very strong correlation.

The interpretation of correlation coefficients followed a commonly cited 'rule of thumb' by Hinkle et al. (2003), however adjustments for lower values were made to correspond with conventions of clothing-specific studies, which generally class correlation coefficients below 0.5 as negligible (e.g. Beazley, 1997; Gupta and Gangadhar, 2004; Gill, 2009), whereas Hinkle et al. (2003) class correlation coefficients below 0.29 as negligible.

Limitations of Study 3

Every research method or strategy has its limitations. The author acknowledges that the findings of this study are not generalisable to the whole population of 20- to 55-year-old females in Manchester who exercise at least three hours a week due to the use of a non-random sampling technique. Non-random volunteer sampling techniques can introduce bias into the sample, however, it was tried to minimise this limitation by using a consecutive sampling approach. The use of non-random sampling is common practice in the field of clinical studies and sports science (Lunsford and Lunsford, 1995; Atkinson, 2012) and was, therefore, appropriate for this study. Especially when considering that the main aim of this pragmatist research project was not generalisability, but rather the creation of new knowledge within a specific context.

It is claimed that volunteer samples are often more highly educated, more socially oriented and more interested in the research topic than the general population (Gratton and Jones, 2010). This had to be considered when analysing the WT questionnaire. However, as most of the collected data were of quantitative nature, there was less risk of bias. All data were collected by the same researcher following rigid procedures, which were described and explained in detail. This increases both the reliability and validity of the study.

As discussed in section 2.5.2.2, some researchers have stated criticism about using pneumatic PM devices, as the air-filled bladder can potentially influence the local body curvature. However, all commercial PM devices have their limitations and selecting a PM device is always a compromise. Pneumatic PM devices are widely used in existing research on SCGs (refer Appendix C) and their accuracy has been shown to be adequate (van den Kerckhove et al., 2007; Mosti and Rossari, 2008; Partsch and Mosti, 2010; Brophy-Williams et al., 2014). For the purpose of this study, i.e. the quantification of pressures under garments in different body postures, the PicoPress® PM device was the best commercially available option.

4.4.3.4 Summary of Data Collected in Phase II

A summary of the data collected in Studies 1, 2 and 3 of Phase II is shown in Figure 4.17. The diagram shows which data were combined and the relationships between data that were analysed (two-way arrows). The data were eventually combined to create a new knowledge base: the findings of Phase II.

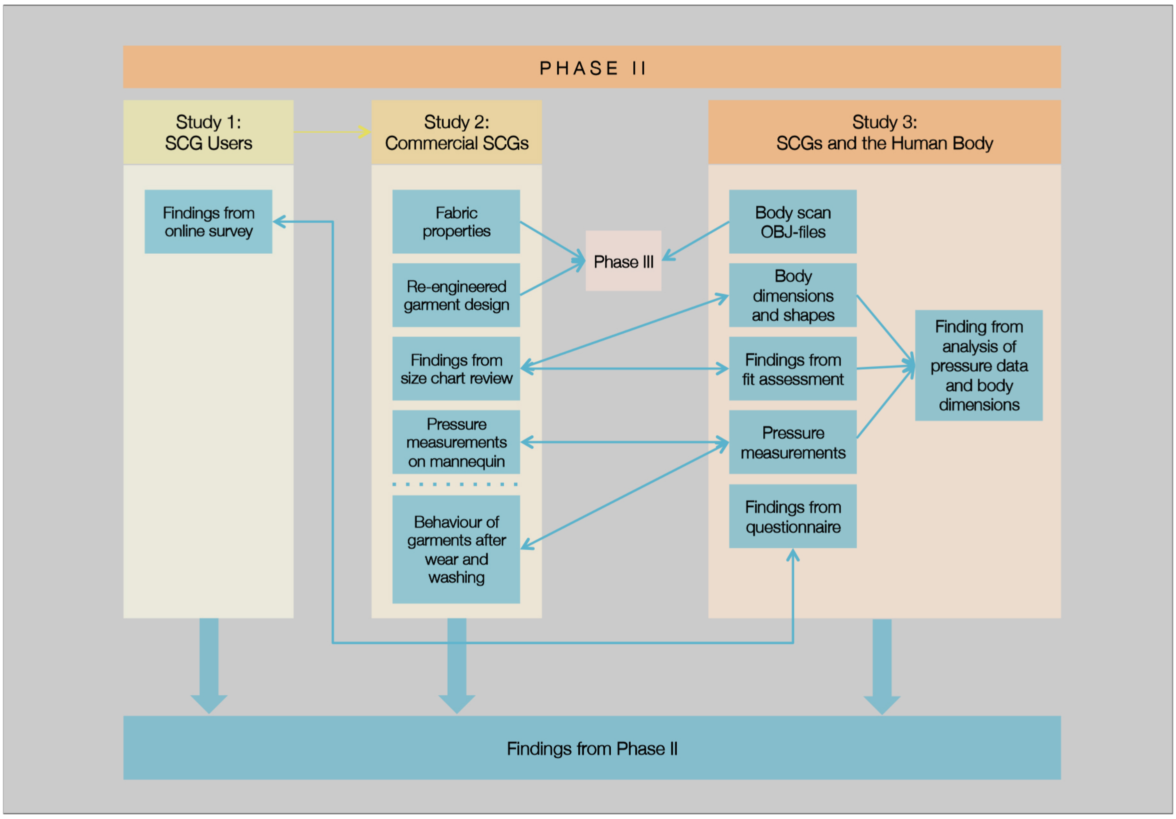


Figure 4.16: Flow of data collected in Phase II of this study

4.4.4 Phase III: Pressure Prediction

With pressures applied by SCGs reported to be varying across individuals (Hill, Howatson, van Someren, Walshe and Pedlar, 2014; Brophy-Williams et al., 2015), there was a need to find a solution that enables control of applied pressures during the design phase. Existing methods to predict the pressures that SCGs apply to a body of known size before a physical garment is produced have been analysed in the literature review (refer section 3.6). Laplace's Law was introduced as a way of predicting pressures. However, it is difficult to apply in the design process by clothing designers and product developers. 3D CAD as a tool to simulate garments by virtually stitching and fitting them onto human avatars is a more familiar concept for designers, as 3D CAD programmes are increasingly adopted by apparel companies.

Most clothing-specific 3D CAD programmes have built-in heat maps denoting pressure or tension that are intended to assist fit assessment by indicating whether a garment fit is too tight on an avatar. It is not known if the pressure maps utilised in 3D CAD programmes are realistic representations of garment pressure.

However, if they were, they would offer a straightforward way of predicting compression, which would facilitate designers' jobs and result in SCGs that apply the desired pressure levels, giving consumers the opportunity to make informed purchase decisions.

Phase III of this research set out to evaluate the use of 3D CAD virtual fit technology to predict pressures in the design process of SCGs by using these pressure maps addressing Aim 5 of this research (see Figure 4.18). The study applied a scientific-experimental evaluation approach using the garment parameters, the anthropometric data and in vivo pressure data obtained in Phase II of this research, as shown in Figure 4.17. With some deficiencies of clothing-specific 3D CAD programmes identified by existing research (refer section 3.6.3.2), the aim of this study was to assess whether it is possible to define a process that could work around current software limitations and apply 3D CAD for pressure prediction in the technical design of SCGs. The objectives of Phase III were as follows:

1. To better understand the effects of different simulation settings on the quality of garment fit simulation and pressure values in heat maps.
2. To compare virtual pressure values to in vivo pressure values.
3. To assess the feasibility of applying 3D CAD virtual fit as a tool for pressure prediction in the technical design process of SCGs.

To achieve Objective 1, the different simulation properties were manipulated in an effort to better understand their relationship to realistic properties and to develop a process that would result in realistic garment fit and pressure outputs. For Objective 2, the WTs conducted in Study 3 of Phase II were repeated virtually by simulating the SCGs from Study 2 using the fabric properties from Study 2 and 15 randomly selected body scan avatars from Study 3. The pressure map tool of the 3D CAD programme was then used to record virtual PMs, which were compared to the in vivo PMs obtained in Study 3. Based on the findings, a judgement was made about the feasibility of using 3D CAD for pressure prediction (Objective 3).

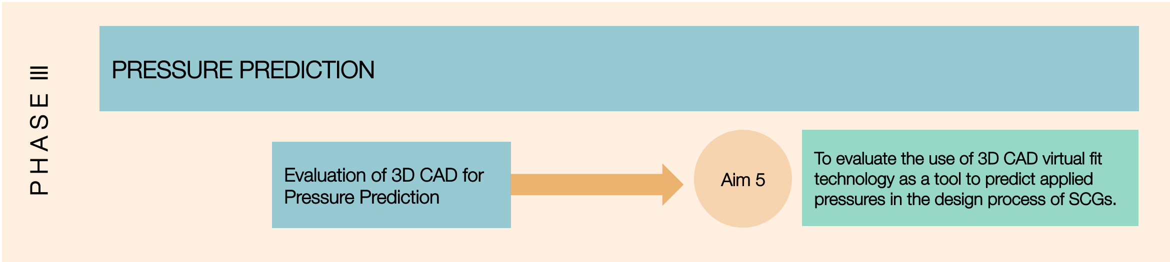


Figure 4.17: Phase III of this study

4.4.4.1 Choice of 3D CAD Programme

Based on the aim of the study, there were a number of requirements for the 3D CAD programme that was to be used for this study. The 3D CAD programme had to:

1. Allow the import of Gerber patterns.
2. Allow the input of fabric data.
3. Allow the import of body scan OBJ-files.
4. Have an integrated pressure map tool that provides numerical pressure values.

The first requirement was necessary because the re-engineered patterns of the SCGs were created in Gerber's pattern making software AccuMark® (Gerber Solutions, USA). The second requirement was important, as the aim of the study was to evaluate the pressure map in the 3D CAD programme and pressure levels are related to fabric properties. The third requirement had to be fulfilled because of limitations to the model morphing tools in most 3D CAD programmes, which do not allow an accurate replication of body dimensions. Finally, the pressure tool within the 3D CAD programme used in this study had to display numerical pressure values in addition to the visual representation of pressures to allow for a comparison and statistical analysis of in vivo and virtual pressure values.

A review of existing 3D CAD programmes and virtual fit had already been conducted as part of the literature review (refer section 3.6.3.2). The developed knowledge informed the decision of which 3D CAD programme to use for the evaluation of virtual fit for pressure prediction. Because this study was building on existing work of Venkatraman et al. (2014) who simulated men's compression tops on built-in avatars using the 3D CAD software VStitcher (Browzwear Solutions Pte

Ltd., Singapore), it was initially planned to use the same software. The VStitcher version available to the researcher was version 6.8, which does not support the input of fabric data unlike earlier versions of the programme that allowed input of fabric properties from the objective fabric measurement systems FAST and KES-F (Kawabata Evaluation System for Fabrics). This feature was removed from the programme as Browzwear introduced its own commercial fabric testing kit, which is in need of standardisation and accreditation (Power, 2013). During initial trials with VStitcher, the researcher encountered problems with importing body scan OBJ-files and Gerber patterns. After consultation with a Browzwear consultant, it was believed that the pattern import issue could have been resolved, however, not the OBJ-file import. The lack of support for OBJ-file import and fabric data input of VStitcher made the software unsuitable for this study.

Several CAD experts in industry and academia were consulted to assess which 3D CAD programme would be more suitable for the purpose of this study. A new release (version 10) of AccuMark® incorporated Accumark 3D, a new 3D design module that works with the open source 3D graphics application Blender (Stichting Blender Foundation, Netherlands). Since the SCG patterns were created in AccuMark®, it was the preferred next choice of 3D CAD programme as criterion 1 was automatically fulfilled. It was further believed that with Gerber, one of the market leaders in garment-specific two-dimensional (2D) CAD, entering the 3D CAD market the software would be at least of the same standard as current systems, if not higher. However, initial trials of simulating basic tops were cumbersome and it was not possible to input fabric data or import OBJ files. The programme only supported fabrics from an existing fabric library and a number of existing avatars, which had limited modification possibilities. The Gerber technical team assured that the next version would be much improved, however, in the current state Gerber 3D was not suitable for the purpose of this study, despite the virtual fit in the linked Blender application having built-in pressure and tension maps providing numerical values.

The 3D CAD programme Optitex Pattern Design Software (PDS) (EFI Optitex, Israel) fulfilled criteria 1, 3 and 4. Like VStitcher, Optitex had recently changed from a fabric convertor tool allowing FAST and KES-F data input to its own Fabric Testing Utility (FTU). Hence, it did not fulfil criterion 2. However, the researcher was unable to identify a 3D CAD programme that fulfilled all four criteria and

Optitex offer a paid service testing customers' fabrics using the FTU. They provide clients with an FDF-file containing the fabric data, which can be imported into Optitex PDS. Eventually, Optitex PDS was chosen as the 3D CAD programme for this study because criterion 2 could be circumvented by having the main fabric of the SCGs (Fabric A) tested by the Optitex FTU. The software version available to the researcher and used throughout this study was Optitex PDS 11, hereafter just referred to as Optitex.

4.4.4.2 Data Import

In order to virtually fit the SCGs to the WT participants' body avatars, the body scan avatar, the graded, re-engineered garment patterns created in AccuMark®, as well as the fabric parameters obtained from the Optitex FTU had to be imported into Optitex.

Body Scan Data

Optitex allows the import of body models in a number of different file formats as shown in Figure 4.19. The RBMs obtained from the body scans were in an OBJ file format and thus could be directly imported into the Optitex software.

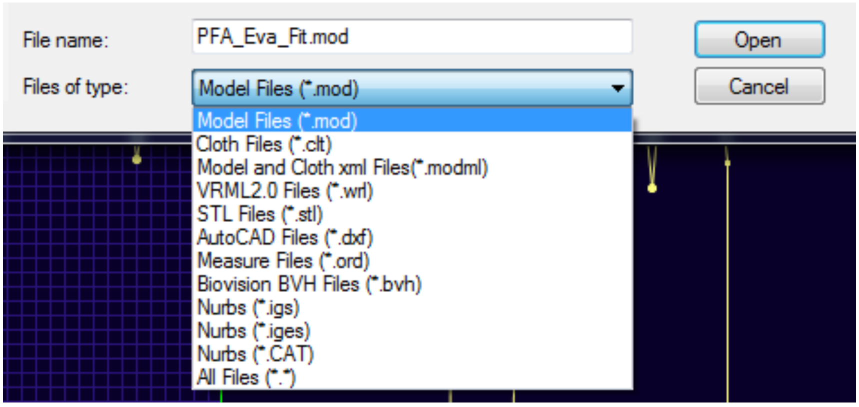


Figure 4.18: Supported file formats for avatars in Optitex

Garment Data

The graded patterns from Study 2 were exported from Gerber AccuMark® in DXF format and imported into Optitex. Once opened in Optitex, the patterns were checked and saved in the Optitex pattern file format (.pds).

Fabric Data

The main fabric of the SCGs under investigation (Fabric A) was sent to Optitex for testing using their own FTU. The other fabrics could not be tested because the samples were too small. The FTU converts fabric properties (weight, thickness, bending, stretch, shear and friction) measured with the FTU into parameters used to simulate fabrics with the Optitex 3D draping algorithm. These parameters are then stored in the Optitex fabric file format (.fdf), which can be added to the existing fabric library in Optitex.

The purpose of the FTU is to provide users with fabric parameters that can be used within the 3D CAD programme to ensure accurate representation of the fabric behaviour. However, the fabric parameters are not meaningful to users in terms of assessing realistic fabric properties because the FTU does not follow accredited test standards. Further details about the tests can be found in Appendix Z.

4.4.4.3 Virtual Fit for Pressure Prediction

The re-engineered compression tights and top patterns were virtually fitted to the body scan avatars using the fabric properties provided by the FTU. There are no publications outlining the details of the virtual fit process, so the researcher utilised knowledge of other 3D CAD programmes combined with instructions provided by Optitex on their online support site and in webinars.

Optitex features four different built-in heat maps to evaluate the fit of simulated garments on body avatars (EFI Optitex, 2011):

- Distance map (mm): Measures the distance between the garment and the body.
- Tension map (g-f/cm): Measures the amount of physical tension by estimating the absolute change of the cloth away from its default shape in either XY-, X- or Y-direction.
- Stretch map (%): Measures the amount of the fabric’s expansion by estimating the percentage change of the cloth away from its default shape in either XY-, X- or Y-direction.

- Normal collision pressure map (dyne/cm^2): Measures the residual collision forces applied to each face in the direction perpendicular to the fabric's mesh in either XY-, X- or Y-direction.

The heat maps visually present variations in the respective characteristic across the body through different colour nuances. As per default settings, minimum values are presented as dark blue and maximum values in red with green and yellow nuances in-between. In addition, there are numerical values shown on the heat map scale bar. When the curser is placed on a point of the simulation, the value for this location is shown on the scale bar. The values of the NCP map are given in dyne/cm^2 and can be converted to 1mmHg (1333.22 dyne/m^2 = 1mmHg). Figure 4.20 shows an example of the normal collision pressure (NCP) map in Optitex.

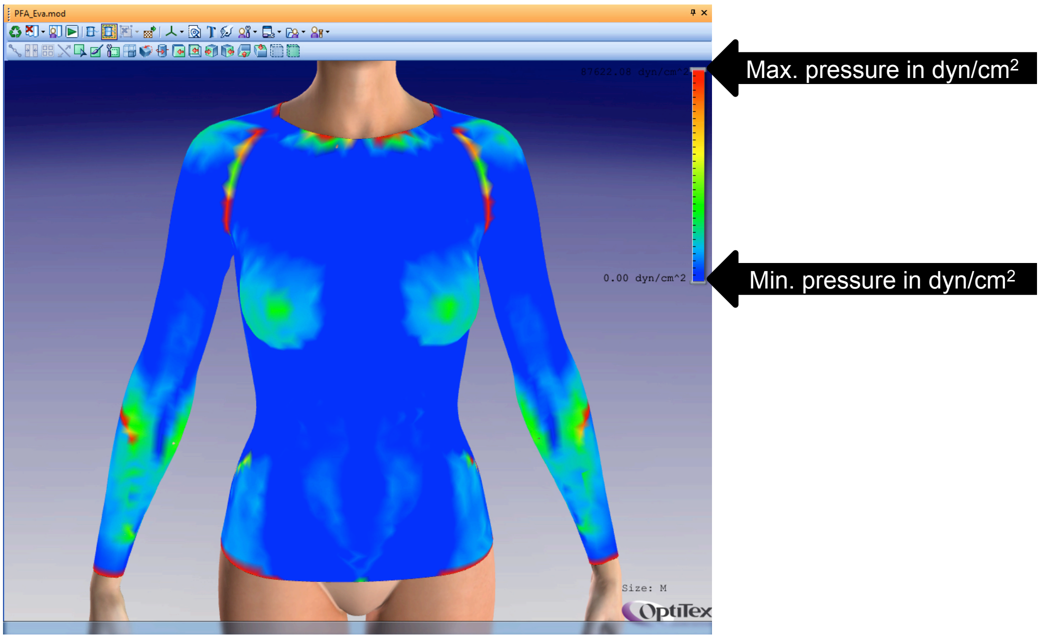


Figure 4.19: Example of heat map (NCP map) in Optitex on a built-in parametric body avatar (screenshot)

Once the SCGs were simulated on a body avatar, the NCP map was used to take virtual PMs with the aim to compare these to the in vivo PMs from the WTs.

4.4.4.4 Simulation Properties

Simulation Settings

3D Properties

Various 3D properties can be set for each pattern piece prior to simulating the garment. Appendix AA shows the 3D properties window in Optitex. The size of a garment can be changed if it is a graded garment and individual pattern pieces can be ignored in the simulation by ticking the ignore box. The positioning properties refer to the position of the pattern piece on the avatar’s body (e.g. front, back, right arm) as well as its shape, i.e. the way it wraps around the avatar’s body (flat, folded, cylinder). The amount and direction (right/left, up/down) can also be defined. If several garments are simulated on an avatar, the layer function determines which garment is located closest to the body (layer 1) and which furthest away from the body. The resolution of each panel, i.e. the number of triangles making up the body mesh, can also be adjusted.

Fabric Parameters

Fabrics from the fabric library can be chosen via the select fabric function. Predefined lists of Optitex fabrics as well as the fdf-file obtained from the FTU can be selected. The parameters are then automatically adjusted based on the selected file, however values can also be input or adjusted manually.

Stitch Parameters

Stitches are defined by three parameters in Optitex: edge force, stitch constant and shrinkage. Edge force is the force of a specified weight pulling the cloth in its direction. The edge force value is directly affected by the fabric’s stretch properties. A fabric with a high level of stretch requires a high level of edge force to pull the cloth in its direction.

The stitch constant refers to the extensibility of a stitch. A high value means a stitch maintains its original length in the simulation and does not extend. The shrinkage of the stitch is the amount of shrinkage in percentage from relaxed to finished stitch. When creating a seam in Optitex, it is possible to select a list of predefined stitch types. The default settings for the three stitch parameters for the different stitch types are shown in Table 4.15.

Table 4.15: Stitch type selections in Optitex and their default stitch properties

Stitch type	Edge force (grf/cm)	Stitch constant (g/cm)	Shrinkage (%)
Lock stitch single needle	0	200	0
Lock stitch double needle	0	250	0
Gathering overlock 2 thread	0	100	25
Overlock 3 thread	0	200	0
Overlock 4 thread	0	200	0
Flatlock	0	200	0
Zigzag	0	100	0

Global Simulation Properties

In addition to the simulation settings related to garment and fabric properties, there are also a number of simulation properties that affect the actual simulation process; here called global simulation properties to distinguish them from the simulation settings that are applied to each individual garment panel. The different parameters and their default values are shown in Figure 4.21.

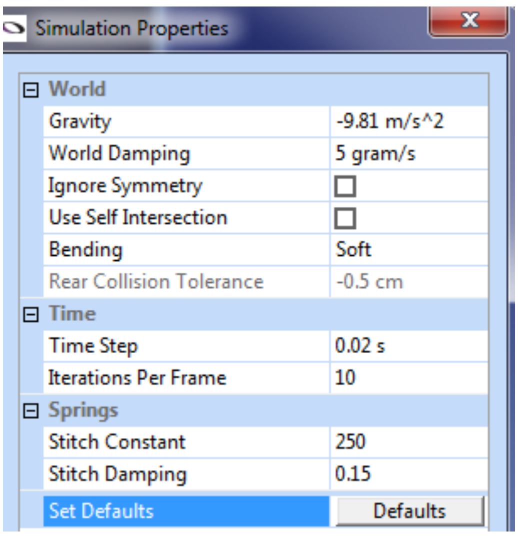


Figure 4.20: Global simulation default settings (screenshot)

All parameters in the 'world' section were not altered by the researcher. However, the 'time' and 'springs' parameters and their effects on simulation were further examined.

Optitex (2011) defines the different parameters as:

- Time step: The constant time interval between the successive positions of the cloth, from the start of the simulation up to the point in which the garment is in rest position.
- Iterations per frame: The number of times the solver is engaged until automatic full stop.
- Stitch constant: Determines the strength of the spring in the stitch.
- Stitch dampening: Determines the stability of the stitch.

Analysis of Simulation Properties

All analyses were conducted using the re-engineered Skins A400 SCGs in size Medium.

Effects of Resolution Settings on Simulation and Virtual Pressure

The effects of different resolution settings on the quality of the simulation were assessed. The resolution refers to the size of the triangles that make up the mesh representing a garment panel. Simulations with low resolution settings use bigger triangles leading to less accuracy in the simulation, whilst simulations with high resolution settings use smaller triangles. Smaller triangles can represent more curved lines and folds in more detail. The speed of the simulation is severely affected by resolution levels. The default resolution setting in Optitex is 1cm. Lower resolution values in Optitex represent a higher resolution, i.e. smaller triangles.

The SCGs were simulated with default resolution settings as well as higher resolution settings and were visually assessed. The main aim was to improve the visual representation of the simulation, as it was advised by an Optitex representative that variations in resolution settings could visually improve simulations.

The high resolution setting with the best visual results was then selected to obtain virtual PMs at locations B31 (calf), B41 (5cm above patella) and B61 (gluteus maximus) by placing the cursor at the locations on the body avatar in the NCP map and recording the value shown on the scale bar. Pressure values were recorded in dyne per cm^2 and converted to mmHg. The same measurements were recorded for the simulation using default resolution settings (1cm) and the resultant pressure values were compared.

Effects of Global Simulation Parameters on Simulation and Virtual Pressure

In order to get an understanding of the impact of global simulation settings on simulation quality and pressure levels in the NCP map, the compression top in size M was virtually fitted to a parametric body avatar in Optitex and the settings for iterations per frame, stitch constant and stitch dampening were changed one at a time, whilst all other values were kept at default settings. The settings used for each parameter are listed in Table 4.16.

Table 4.16: Settings used for each global simulation parameters

Global simulation parameter	Settings used for analysis
Time step	0.1, 0.2 (default)
Iterations per frame	10 (default), 20, 30
Stitch constant	100, 150, 200, 250 (default), 300, 350, 400, 450, 500
Stitch damping	0.05, 0.15 (default), 0.25

Resolution was set at the default 1cm level, whilst the fabric parameters from the Optitex FTU were applied. The simulation quality was assessed visually by recording problems with fabric gaps or fabric fold. The maximum pressure values were recorded from the NCP map.

Effects of Fabric Parameters on Virtual Pressure

To get an idea of how the different fabric parameters used in Optitex affect pressure levels in the NCP map, the compression top in size M was simulated on a body avatar and all fabric settings were initially set to the values provided by the Optitex FTU. The global simulation and resolution settings were kept as per the default settings, whilst the stitch settings were set as 0/100/0 (edge force/stitch constant/shrinkage), except for the hem, which was set as 30/50/4. The different fabric parameters - bending, stretch, shear, friction, thickness and weight - were changed one parameter at a time, whilst all other settings remained as described above. The settings used for each parameter are listed in Table 4.17.

Table 4.17: Settings used for each fabric parameter

Fabric parameter	Settings used for analysis
Bending X, Y (dyne•cm)	5 to 100 with 5 point increments
Stretch X, Y (gf/cm)	50 to 500 with 50 point increments
Shear (dyne/cm)	10 to 100 with 10 point increments
Friction	0.1 to 1 with 0.1 point increments
Thickness (cm)	0.01 to 0.1 with 0.01 point increments
Weight (gsm)	150 to 400 with 25 point increments

Once the garment was simulated with each new setting, the pressure was recorded from the NCP map at PM locations T11 (hem at centre front) and T51 (shoulder blade) by placing the cursor on the pressure map and reading the pressure value off the pressure scale bar. Pressure values were recorded in dyne per cm^2 and converted into mmHg.

Effects of Stitch Parameters on Virtual Pressure

The effects of the two stitch parameters stitch constant and shrinkage on virtual pressure values in Optitex were assessed by virtually fitting the compression top to a parametric model and changing one of the stitch parameters at a time. The settings used for each parameter are listed in Table 4.18.

Table 4.18: Settings used for each stitch parameter

Stitch parameter	Settings used for analysis
Stitch constant (g/cm)	0 to 1000 with 100 point increments
Shrinkage (%)	0 to 90 with 10 point increments

The fabric settings were set to the Optitex FTU test results and the simulation and resolution settings were left in the default settings. Shrinkage was set at zero for the stitch constant analysis. The shrinkage analysis was performed twice once for stitch constant 200g/cm and once for stitch constant 100g/cm. Once the compression top was simulated with each setting, the maximum pressure value and the pressure at PM location T131 (sleeve hem at inner wrist) were recorded from the NCP map.

4.4.4.5 Virtual Wearer Trials

The key aspect for the evaluation of the feasibility to use the Optitex NCP map to predict pressures applied by SCGs lay in the analysis of in vivo and virtual PMs. If a correlation existed between these PMs, the NCP map could potentially be used in the design of SCGs. The WTs from Phase II of this study were, therefore, repeated virtually. The remodelled body avatars of 15 WT participants were imported into Optitex and the re-engineered Skins A400 compression tights and top were virtually fitted to the body avatars. Pressure values were recorded from the NCP map by placing the curser on each PM location and recording the pressure value shown on the pressure scale bar. Due to potential inaccuracy in pinpointing the exact PM location on the body avatar, the mean of three pressure readings was used for analysis. Values were recorded in dyne per cm^2 and converted to mmHg. Measurements from the tension maps were also recorded to find out whether there is a relationship between the tension and pressure values that could be of use for pressure prediction.

Reliability Check

Reliability checks of the simulation process in Optitex were undertaken to check that repeat simulations of the same pattern file on the same avatar file would lead to the same simulation result. For this purpose, the 15 compression tights and top pattern files used for this study with the individual 3D positioning on the body for each avatar were re-simulated at three different occasions using the same avatar. Further, the tension and pressure maps were checked to ensure that results are repeatable.

Virtual Pressure Analysis

For the virtual pressure measurements the same PM locations that were used in the WTs (refer Appendix N) were used. The resulting pressure values were statistically analysed using IBM® SPSS® Statistics (Version 24). Wilcoxon signed-rank tests were applied to identify if the pressure values varied significantly across different simulation settings, whilst Spearman’s rho correlation tests assessed the relationship between the Optitex NCP and tension maps and the garment stretch percentage values measured in Study 2 of Phase II of this research.

In Vivo vs. Virtual Pressure

The in vivo pressure data obtained from the WTs were compared to the virtual pressure data. As the pressure data were non-normal, Spearman’s rho correlation tests were run to detect correlations between the in vivo and virtual pressure values at each PM location. Wilcoxon signed-rank tests were conducted to check whether the in vivo and virtual pressure values varied significantly. In an attempt to find correlations that could support the use of the Optitex NCP or tension maps for pressure prediction, Spearman's correlations were also run to assess the relationships between the NCP and tension maps and body measurements of the avatars.

4.4.4.6 Limitations of Phase III

The evaluation of virtual fit for pressure prediction was limited by the restrictions of the 3D CAD software Optitex. The manipulation of the various simulation parameters relied on the researcher's judgement since there were no clear links between the parameters applied by Optitex and physical garment properties.

There were limitations in reading the pressure values off the pressure map. In order to be comparable to in vivo measurements, the pressure values needed to be taken at the same locations on the body. However, identifying the exact location on the avatar was difficult. As the mouse curser was placed over the identified locations, the reading had to be taken from the scale. When moving the mouse curser slightly, pressure values varied considerably. To reduce this limitation, the mean of three pressure readings was used for the comparison with the in vivo PMs.

As identified by previous research (Lim, 2009), visual appearances of simulations with identical fabric properties can differ using different 3D CAD programmes. Hence, the findings of this study are limited to the Optitex software and version used in this study. Judgements about the feasiblity of using Optitex as tool for pressure prediction are further only valid for the simulation settings used in this study.

4.4.5 Phase IV: Design Framework

Phase IV was a critical phase of the study, as all the key findings from the subsequent phases were drawn together and synthesised to define design principles and a design framework for SCGs to fulfil Aim 6 of this research (see Figure 4.22).

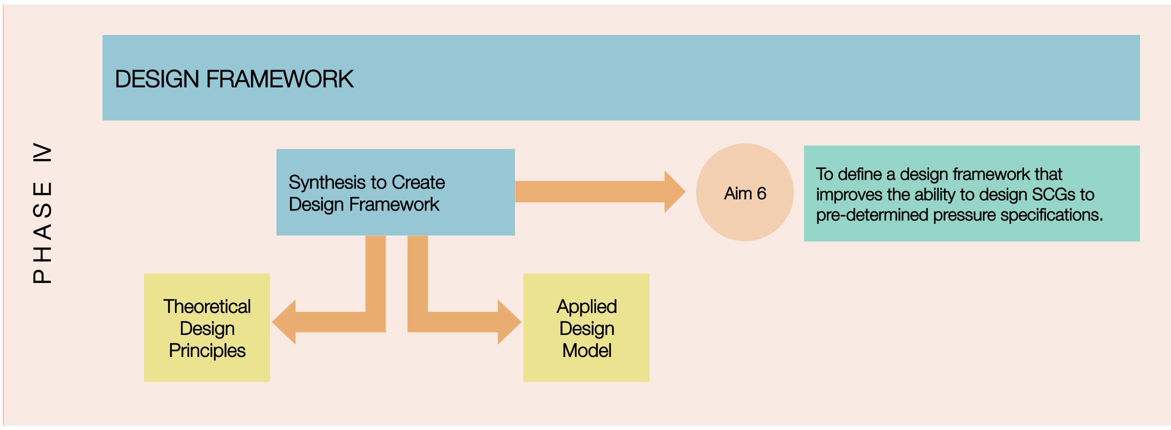


Figure 4.21: Phase IV of this study

During the synthesis process the researcher viewed the findings and their relation to SCGs through three different lenses: the process lens, the user lens, and the product lens. Viewing the collated findings through these specific lenses allowed the researcher to define design principles and develop a design framework relevant to each of the three areas that are critical in the design of SCGs (refer Figure 4.23).

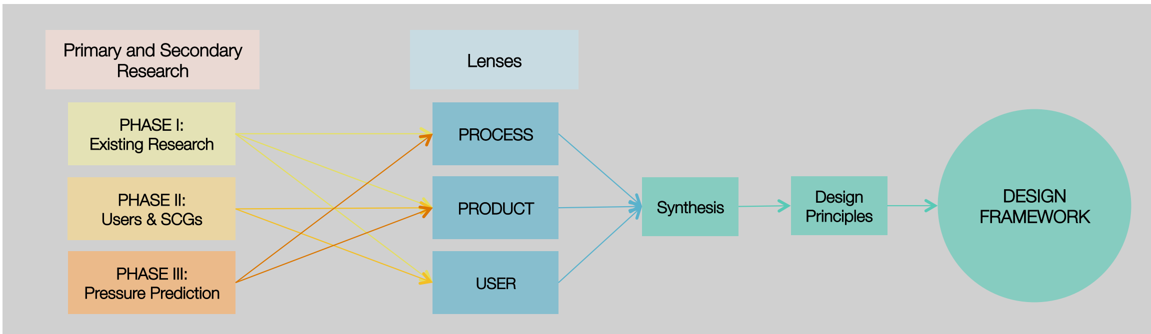


Figure 4.22: Strategy for definition of a SCG design framework

Based on the pragmatist research approach of this study, the design principles and final design model that concluded from this study were intended to be relevant in design research and practice. It was aimed to develop a design framework that would eventually lead to improved SCGs by, on the one hand, enhancing the theoretical knowledge base, which was hoped to lead to more holistic and better-informed research on SCGs and, on the other hand, defining a framework that could be applied in the practical design of SCGs, which was hoped to facilitate the design of improved SCGs.

4.5 Ethical Considerations and Risk Assessment

Ethical approval for the study was obtained from Manchester Metropolitan University on 2nd April 2015. The study was conducted by an independent researcher with no conflicts of interests.

Only the online survey (Study 1) and the WTs (Study 3) of Phase II of this research involved participants. All individuals participated in the studies voluntarily. The link to the online survey was distributed online and participants chose to respond to the online survey out of free will. The same is true for the WTs. Participants were not coerced to take part in the WTs, in the contrary; individuals approached the researcher via email based on recruitment posters. The researcher then sent the WT information sheet to the potential participant and encouraged her to ask any additional questions she might have. If the individual did not respond to the email, the researcher did not follow up. It was assumed that the individual was not interested in participating in the study. This procedure was thought to be the most ethical approach as any element of coercion was eliminated.

Once participants had agreed to take part in the WTs and a suitable time for the WT was arranged. The participants were given the chance to read the information sheet again at the start of the WT and were given the opportunity to ask questions. The participants were informed that they could end their participation in the study at any point without stating a reason. Once the participants stated that they had no further questions and were happy to go ahead with the discussed WT, they signed the consent form.

Since the WTs involved a 3D body scan in underwear, various ethical issues had to be considered. Established ethical protocols for 3D body scanning were applied, which meant that at least one technician was present at all times during the WTs. Concerns regarding partially clothed participants were considered in the protocol. There was a private changing cubicle and a modesty curtain around the 3D body scanner. A dressing gown was provided for the participants to wear and it was only removed for the body scan in underwear when the modesty curtain was closed to ensure privacy. Measurement capture with the 3D body scanner is non-contact and non-invasive.

The body scan data recorded during the WTs were stored anonymised for an unlimited timeframe by the researcher. The body scan data were additionally stored in the institutional database in order to accumulate statistics, where it might be used for internal future research. Participants were informed about the storage of their coded data on the participant information sheet and agreed to this by signing the consent form. The participants were, however, informed that they could request that their data be removed from the database at any point in time.

In addition to the 3D body scans, photographs of the participants wearing the SCGs were taken during the WTs. This was identified as a potential ethical issue. However, photographs were taken without recording participants' faces and were stored anonymised. This was believed to eliminate any ethical concerns with taking photographs.

The signed consent forms and physical recordings from the WTs were all kept in a locked office cabinet on the University campus. All online survey respondents were anonymous.

No risks or hazards were identified for the research, as the researcher was not a lone worker. Technicians were always present when working in laboratories and standard protocols were followed at all times. There was also no identifiable risk for the participants, as the SCGs worn in the WTs were commercial SCGs applying comparatively low levels of pressure. Therefore, participants were not exposed to any additional risk. There was also no risk associated with PMs using the PicoPress® PM device. It is a well-established measurement instrument that is commonly used in clinical settings to measure bandage pressure. None of the activities caused any discomfort, danger or interference with normal activities for the participants or the researcher. Care was taken to make the WT experience as enjoyable as possible for participants.

4.6 Chapter Summary

This chapter has provided the rationale and operational details of the methodological framework and research strategy that was applied in this study to achieve each of the research aims. The study was rooted in pragmatism and informed by the principles of Pasteur's Quadrant, Interdisciplinarity and Design

Science Research. The multi-method quantitative strategy was based on an inductive approach. The research was divided into four phases:

- Phase I: Existing Research,
- Phase II: Users & SCGs,
- Phase III: Pressure Prediction,
- Phase IV: Design Framework.

Phase I: Existing Research

Phase I of this study was an extensive review of existing research on SCGs and related subjects. The literature review was part of the analysis stage of the study and aimed to give an accurate profile of the theoretical knowledge base of SCGs. The literature search put the research into context and helped to further specify the research problem and knowledge gaps. Phase I fulfilled Aim 1 of the study.

Phase II: Users & Sports Compression Garments

Phase II was the primary data collection phase of the study and was related to the 'real world'. 'Real world' findings were critical to the pragmatist approach of this study, as the methodological approach of this study demanded theoretical as well as practical input. The research phase was divided into three studies:

- Study 1: SCG Users
- Study 2: Commercial SCGs
- Study 3: SCGs and the Human Body

Study 1 applied an online survey to get insights into SCG users' wear behaviour, their product preferences and their attitudes towards SCGs. Study 2 analysed the properties of commercial SCGs in relation to fabrics, garment construction and sizing, whilst Study 3 was concerned with the relationship of SCGs and the human body. This relationship was analysed in WTs with 33 female participants. The findings of Studies 1, 2 and 3 fulfilled Aims 2, 3 and 4 of this research.

Phase III: Pressure Prediction

Phase III was an evaluation of the use of virtual fit technologies for pressure prediction. The 3D CAD programme Optitex was used for this purpose. The garment parameters obtained in Study 2 and the anthropometric data and physical pressure data from Study 3 of the preceding research phase were used for the evaluation. The evaluation of virtual fit technologies for pressure prediction fulfilled Aim 5 of the study.

Phase IV: Design Framework

The findings from Phases II and III were synthesised with the findings from the theoretical knowledge base (Phase I) in order to translate the findings into principles and a framework for the design of SCGs that would facilitate the design of SCGs with controlled pressure.

The chapter also addressed the limitations and potential ethical issues of this research and illustrated the approaches used to minimise potential criticism.

5 FINDINGS FROM PHASE I: EXISTING RESEARCH

5.1 Chapter Introduction

This chapter presents the findings emerging from Phase I: Existing Research (Chapters 2 and 3) in relation to the research field of SCGs. It proposes a research overview map of the multidisciplinary field of SCGs and identifies research gaps, whilst highlighting how these will be addressed by this research project.

5.2 Sports Compression Garments as a Topic of Research

The increasing popularity of sports compression garments (SCGs) and the growing market has caused an influx in research on SCGs. A new field of research emerged that was shaped by sports scientists who were keen to evidence the effects of SCGs on various aspects of exercise and post-exercise recovery. However, the single-disciplinary approach of existing SCG research has neglected various aspects that are critical for functional SCGs. The comprehensive review of existing literature (Chapters 2 and 3) from all fields relevant to SCGs highlighted the multidisciplinarity of the research field of SCGs as well as the complexity of designing SCGs with controlled pressure.

At the outset of the literature review, the identified studies were scanned and broadly divided into different themes. As part of this initial exploration of the research topic of SCGs, four preliminary themes emerged, which were broken down into subthemes as presented in Table 5.1.

Table 5.1: How this study will address gaps in the research field of SCGs

Compression Garments for Athletes	
A. Textile Technology	Fibres and finishes
	Extension and recovery
	Thermal regulation
	Moisture management
B. Sports Science	Body physiology
	Pressure points
	Performance measurement
	Sports psychology
C. Clothing Technology	Garment design

Compression Garments for Athletes	
	Sizing
	Manufacturing techniques
	Performance testing
D. Technology and Simulation	3D Body scanning
	CAD
	Pressure mapping
	Virtual fit

As the review of existing literature developed, the themes developed and expanded. Refinement of the most critical themes and subthemes enabled the creation of an overview map of the research topic of SCGs as presented in Figure 5.1.

As is evident from Figure 5.1, the subject of SCGs is multidisciplinary with related fields ranging from sports science to clothing design, textiles, physics, medical science as well as technologies and processes applied. Research in these fields directly or indirectly influences the theoretical knowledge base of SCGs. Understanding these relations is critical to appreciate the complexity of SCGs and some of the controversies in existing SCG research.

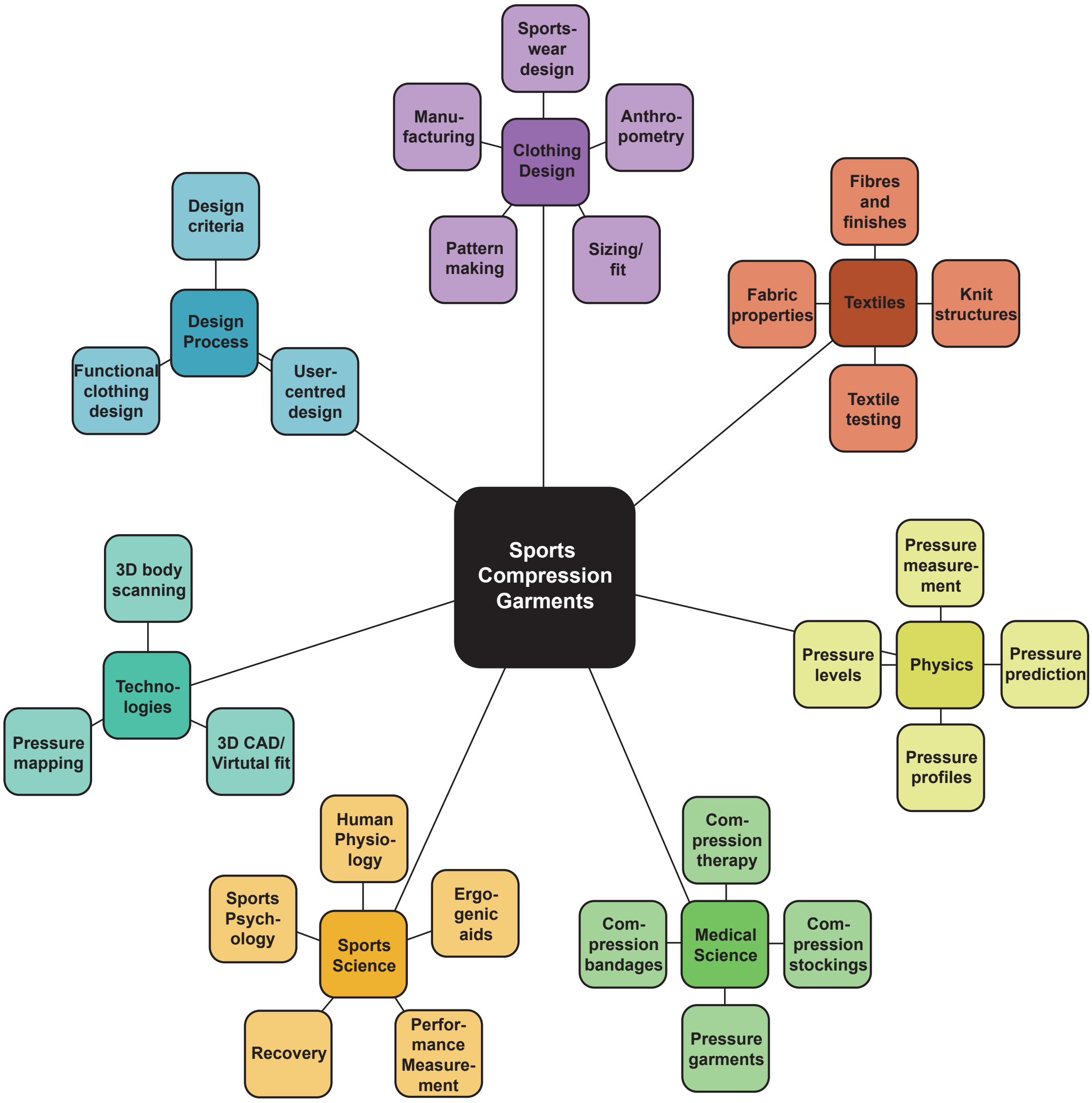


Figure 5.1: Overview of the research field of SCGs

5.3 Research Gaps

Due to the interdisciplinary nature of the study, it was essential to view SCGs from the perspectives of the different disciplines related to SCGs. It became apparent that most of the exsiting research on SCGs was conducted in the sports science and medical disciplines, whilst there was only limited research published in the clothing or textiles disciplines. The most critical part was that there was no cross-fertilisation between the different disciplines, so clothing and textile related aspects were mostly neglected in studies from the sports science or medical fields. Due to this single-disciplinary approach, many topics related to SGCs have not been researched in the context of SCGs, so the literature review drew on general studies in these fields and related concepts to the SCG context. This led to a broadening of the interdisciplinary researcher's perspective on these topics.

With the developed research overview map (Figure 5.1) it was easy to categorise research studies and identify research gaps. Figure 5.2 highlights the research areas with some research in relation to compression garments (CGs), but no clear evidence (grey circle) and the areas that have been covered more widely by research in the context of CGs (orange circle). Areas without circles lack any research in relation to CGs.

There are currently no known studies that investigate the psychology of SCGs during exercise. Likewise, there is a lack of research on garment development aspects of SCGs, such as grading and sizing, manufacturing techniques and the product development process for SCGs.

Figure 5.2: Gaps in the research field of SCGs

Existing research on the functionality of SCGs frequently fails to measure applied pressures, only reporting manufacturer's pressure indications. This makes the findings of the studies of limited use. Compression pressures are dependent upon the location of the garment in respect to the human body and inherent inter-individual variability (Hill et al., 2015; MacRae et al., 2016). The few researchers that analysed pressure profiles in detail (e.g. Brophy-Williams et al., 2015; Hill et al., 2015) found inconsistencies in the pressure levels and profiles across individuals. This indicates that the pressure distribution of SCGs is currently not well controlled and highlights the need for research on the design of SCGs.

Whilst there is currently no agreed 'optimal' pressure level or distribution pattern, it is crucial to know pressure values to interpret results and compare studies (MacRae et al., 2016). Compression should be regarded as the 'dosage' of compression treatment. It is surprising that researchers have been neglecting compression for so long and are only starting to realise the importance of quantifying compression. It appears that researchers have underestimated the difficulty of achieving controlled pressure application (Tyler, 2015).

Mechanical properties of SCGs determine the level of pressure applied to the body. The two key garment elements affecting pressure are the structure and physical properties of the fabric and the fit of the garment on the body. Fabric characteristics, such as fibre blend (i.e. amount of elastic fibres), yarn fineness and fabric construction, affect compression levels. Fit depends on the garment construction, the sizing system applied and the wearer's body. The effects of body size and shape on fit and sizing and therefore the effectiveness of SCGs have not been studied. It is not known whether existing SCG sizing systems account for the variations in size and shape resulting in the intended level and profile of pressure. There is no research to date exploring this field of SCG research, however, studies on medical graduated compression stockings show that the level of intended pressure often varies from measured pressure (e.g. Wildin et al., 1998; Best et al., 2000).

In order to design SCGs to desired pressure specifications, it is necessary to predict pressures in the design phase. Only few researchers investigate aspects of designing SCG pressure profiles. There is theoretical research on pressure prediction using Laplace's Law (e.g. Troynikov et al., 2010; Macintyre and Ferguson, 2013) for tubular garments, however, no practical models for complex SCGs exist. Salleh and colleagues (2012) suggested a mathematical model for the development of customised SCGs. The model requires the input of body scan data, fabric modulus of extension and the desired pressure level and is able to create a simulation of a customised SCG, which could be used to develop garment patterns. Similar simulation methods are available using 3D CAD programmes, such as VStitcher (Browzwear Solutions Pte Ltd., Singapore), as was attempted by Allsop (2012). The approaches show potential for the design development of SCGs, however, further research is required to make these attempts usable in practice.

The interrelations of the construction of a garment and its fit, fabric properties, size and shape of the wearer's body and the movements undertaken by the wearer affect the level of pressure exerted by SCGs and through this their functionality (Troynikov et al., 2010). Whilst there are isolated studies in some of the research fields critical for SCGs, there are no studies that take a holistic approach to SCG development considering all these aspects. There is further no research considering the whole complexity of technical and procedural aspects of the design development process of SCGs.

For the successful design of SCGs it is essential that the following knowledge gaps be addressed:

- Consideration of users' perception and psychology of wearing SCGs,
- Practical models for pressure prediction,
- Optimal pressure levels for performance and recovery,
- Effects of movement on pressure,
- Design of SCGs for optimal comfort,
- Design of SGCs to user needs,
- Grading and sizing of SCGs,
- Manufacturing techniques for SCGs,
- SCG design processes.

5.4 Chapter Conclusions

This Chapter presented an overview map of the multidisciplinary research field of SCGs that emerged as a result of the search and analysis of the topic of SCGs and existing research on SCGs as part of the literature review (Chapters 2 and 3). This interdisciplinary study was the first to identify all relevant research fields that indirectly or directly affect the design of SCGs. The chapter highlighted problems with current single-disciplinary approaches that do not cross-fertilise across different fields and thereby neglect important aspects when designing studies and interpreting findings.

The developed overview map facilitated the identification of research gaps in current literature. Table 5.2 summarises how the identified research gaps will be addressed by this study, which, through this, will make a significant contribution to the knowledge base of SCGs.

Table 5.2: How this study will address gaps in the research field of SCGs

Identified research gap	How this gap will be addressed by the study
No consideration of users' perception and psychology of wearing SCGs	Knowledge about the perceptions and attitudes of athletes towards SCGs is essential for the design of SCGs and is, therefore, addressed by Aim 2.
No practical models for pressure prediction	This study will build on the existing research and further develop it by defining a framework for the design of SCGs that incorporates variations of these methods and makes them easily applicable in the apparel industry.
No optimal pressure level	Scientific studies in the sports medical field are needed to further investigate this issue. This research exceeds the scope of this study.
Effects of movement on pressure not understood	The study will conduct wearer trials that will quantify differences in levels of applied pressure in different body postures.
No research on how to design SCGs for optimal comfort	The study will assess comfort levels of commercial SCGs in wearer trials and consider garment characteristics that can improve comfort.
No guidance on how to design SGCs to user needs	This study addresses this knowledge gap by addressing user needs. The final theoretical outcome of the proposed study will include design principles for the development of SCGs, which will benefit compression sportswear designers. Aim 5 of this study will evaluate the use of virtual fit for pressure prediction.
No studies on grading and sizing of SCGs	The study will examine grading and sizing techniques applied for SCGs by analysing commercial SCGs (Aim 3).
No studies on manufacturing techniques for SCGs	This study will address this gap in the literature review and by examining commercial SCGs.
No research on SCG design processes	This knowledge gap will be addressed by Aim 6 of this study by defining a framework for the design development of SCGs.

6 FINDINGS FROM PHASE II – STUDY 1: SPORTS COMPRESSION GARMENT USERS

6.1 Chapter Introduction

This chapter presents and discusses the results of Phase II – Study 1: Sports Compression Garment (SCG) Users. Study 1 applied an online survey to identify SCG users' wear experiences, product preferences and attitudes towards SCGs, fulfilling Aim 2 of the research project.

6.2 Objectives of Online Survey

The objectives of the online survey were:

1. To identify the way the survey respondents use SCGs.
2. To determine the survey respondents' attitude tendencies towards SCGs.
3. To identify needs and product preferences of the survey respondents.
4. To establish whether commercial SCGs fulfil the needs and expectations of the survey respondents.

6.3 Results of Online Survey

6.3.1 Survey Respondents

233 survey responses were collected over a period of one month. A list-wise deletion process was used to only include fully completed questionnaires for analysis. 200 completed questionnaires remained for analysis out of which 145 were completed by SCG users. The remaining 55 responses were from non-SCG users who were asked for their reasons for not using SCGs as part of their training routine. These responses were grouped by themes. Almost a third (29.1%) of the non-SCG users stated that they did not feel the need for them. 21.8% commented that they did not see or believe in the benefits of SCGs, while 16.4% of the non-SCG users stated that they were unfamiliar with SCGs and the benefits that they could offer them. Other factors that stopped the respondents from using SCGs were comfort-related issues (10.9%) and the high price of SCGs (9.1%).

The 145 respondents who used SCGs completed the remaining survey questions and were included in below analysis of results. As stated in 4.4.3.1, the survey included both female and male respondents in order to identify whether there were any differences in wear behaviour, preferences or attitudes towards SCGs across genders. The age and gender distribution of the included survey respondents are shown in Figure 6.1.

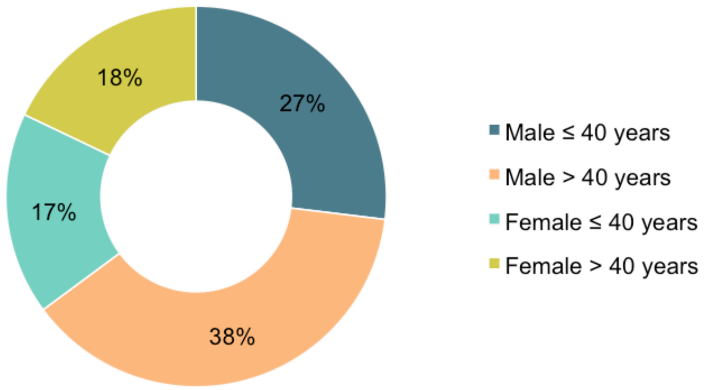


Figure 6.1: Gender and age of survey respondents included in analysis (*n* = 145)

Initially there were four age categories, however, they were collapsed into two as the number of respondents in the lowest and highest group was very low (3 respondents in the <20 group and 7 in the >60 group). The age distribution was relatively even, however, there were slightly more respondents in the over 40 age group (55.9%). The highest represented group were males over the age of 40. 93.8% of respondents resided in the UK with 4.8% living in Europe and 1.4% in Australia. Because of the small number of respondents from outside the UK, no distinctions were made in the analysis of the survey data.

The vast majority of respondents (93.1%) participated in running-related sports, with the remaining sports being team sports (5.5%), cycling (0.7%) and cross fit (0.7%). With an average of 6-7 hours of training a week (*Md* = 6, *M* = 7.2) and only 11.5% of respondents training more than 10 hours a week, the majority of respondents could be classed as recreational athletes. More than half (59.3%) of the respondents had trained less than 5 years at the stated frequency. 95.9% of respondents participated regularly in competitive events with a median of 10 competitive events over the 12 months preceding the survey. More than two thirds (69%) competed at recreational or club level, whilst 28.9% of respondents competed at a higher level (regional, national or international). Refer to Appendix BB for further details.

It is important to keep the demographic tendency towards males aged over 40 and the average training status of the respondents in mind when analysing the data, as responses from other demographics and more professional athletes could result in different outcomes. To avoid any bias in drawing conclusions, crosstabulations and correlations were calculated, where possible, to find out whether there are any variations across different demographics and training levels. The findings are valid for fitness-related sports and are not generalisable to other sports disciplines.

6.3.2 Wearer Behaviour

SCG types mostly worn by survey respondents were socks (51.7%), long tights (44.1%), shorts (41.4%) and long sleeve tops (29%). There was a clear tendency towards lower body SCGs. Among all the 342 garments mentioned, 74.3% were lower body garments, 24.9% were upper body garments with the remainder (0.9%) being body suits.

A crosstabulation of gender and garment types (see Appendix CC) showed that long tights were the most popular garment type among females, followed by socks and shorts. Male respondents favoured the same garment types, however, long tights were less popular compared to females (37.2% compared to 56.9%). 64.8% of respondents stated that they wear SCGs ‘always’ or ‘often’ during training, while 60.7% ‘always’ or ‘often’ wear them during competitive events. Less than half of the respondents (41.4%) stated that they ‘always’ or ‘often’ wear SCGs during recovery (refer Figure 6.2). Chi-square tests for independence were conducted to find out whether there is a significant association between wear frequency and gender or age. A significant association was only found between wear frequency during competition and gender, χ^2 (df = 4, n = 145) = 10.366, p = 0.035, Cramer’s V = 0.267 (effect size: small = 0.10, medium = 0.30, large = 0.50). 72.6% of female respondents ‘always’ or ‘often’ wear SCGs during competitive events, compared to 54.3% of male respondents.

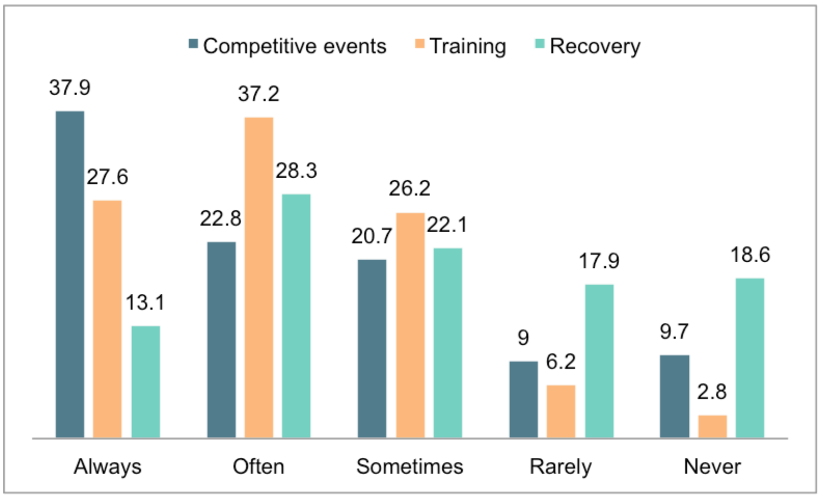


Figure 6.2: Wear frequency of sports compression garments (%; *n* = 145)

The average wear time per use of SCGs by respondents lay between 2.6 and 3.7 hours (95% confidence interval for mean). 66.2% of the respondents reported wearing their SCGs for two hours or less, whilst only 3.5% wear them for more than eight hours. About half of the respondents (51%) wear additional clothes over SCGs, thus treating them as base layers. This number varied significantly among male and female respondents (66% and 23.5% respectively). This was confirmed by a chi-square test for independence (with Yates's continuity correction), which indicated a significant association between wearing additional clothing over SCGs and gender, χ^2 (df = 1, n = 145) = 22.149, $p < 0.001$, phi = 0.405 (effect size: small = 0.10, medium = 0.30, large = 0.50). Based on the odds ratio, the odds of wearing additional clothing over SCGs was 6.30 times higher in males than in females. There was no significant association between wearing additional clothing over SCGs and age. The most popular clothes worn over SCGs by the survey respondents were loosely fitted T-shirts and shorts.

The main reasons for wearing SCGs reported by both male and female respondents were reduction of post-exercise muscle soreness, injury prevention, faster recovery, followed by improved comfort (refer Figure 6.3). Extending time to fatigue and reducing muscle vibration were also reasons for wearing SCGs for about a quarter of both sexes.

The response choices listed in Figure 6.3 were based on claims made by SCG brands and were ordered based on response frequency. It is noticeable that the most popular responses were related to physiological effects of wearing SCGs, such as reduced muscle soreness and injuries and faster recovery, whilst the second most popular group of responses were related to the feelings whilst wearing SCGs, such as improved comfort and temperature control. A third theme emerging from these responses was related to aesthetics, including enhanced figure appearance and strength.

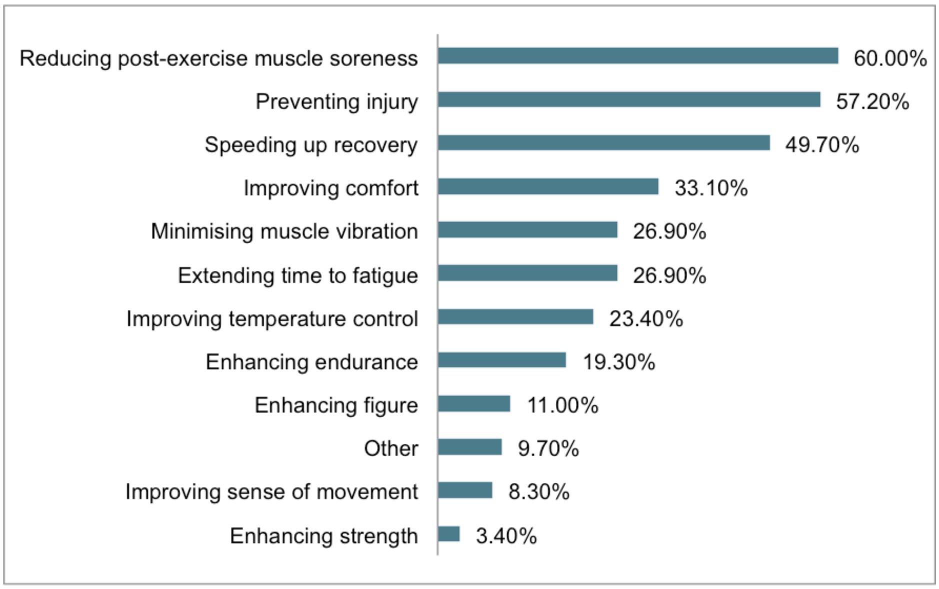


Figure 6.3: Reasons for wearing sports compression garments for survey respondents (*n* = 145)

6.3.3 Attitudes

To analyse the attitude scale, the total sums of scores for each individual was calculated. The reliability of the scale was checked using Cronbach's alpha and mean inter-item correlations (Appendix DD). According to DeVellis (2012), Cronbach's alpha values over 0.7 represent good results and Briggs and Cheek (1986) stated that inter-item correction values between 0.2 and 0.4 are desirable. Since the attitude scale resulted in a Cronbach's alpha value of 0.842 and mean inter-item correlation value of 0.313, it was concluded that the attitude scale was reliable.

The total possible score of the attitude scale was 60, which would indicate a very positive attitude towards SCGs. The mean score of all respondents was 39.4, in other words 65.7% of the total possible score. This indicates a positive tendency towards SCGs among the survey respondents. However, only 49% of respondents stated that they believe that SCGs improve performance, in contrast to 77.9% who believe that SCGs improve recovery. Using chi-square tests for independence (refer Table 6.1), no significant association could be found between the belief in the performance-enhancing properties of SCGs and gender (BP1), age (BP2), training hours (BP3), years of training (BP4) or competition level (BP5). The same is true for the recovery-enhancing properties of SCGs and gender (BR1), age (BR2), training hours (BR3), years of training (BR4) or competition level (BR5). There were further no significant associations between the belief in these properties and the wear frequency during competitions and training. However, a chi-square test for independence indicated a significant association between wear frequency during recovery and the belief in recovery-enhancing properties of SCGs, χ^2 (df = 4, n = 145) = 27.823, p < 0.001, Cramer's V = 0.438 (effect size: small = 0.01, medium = 0.30, large = 0.50).

Table 6.1: Results of chi-square tests for independence (n = 145)

	df	χ^2	*phi*	Cramer's *V*	*p*
BP1	1	.00	-.001	N/A	1
BP2	1	.079	-.037	N/A	.779
BP3	2	.327	N/A	.047	.849
BP4	3	2.351	N/A	.127	.503
BP5	5	4.806	N/A	.182	.440
BR1	1	.542	-.079	N/A	.462
BR2	1	3.114	-.163	N/A	.078
BR3	2	2.643	N/A	.135	.267
BR4	3	6.712	N/A	.215	.082
BR5	5	8.821	N/A	.247	.116

Case summaries of the respondents' belief in performance- and recovery-enhancing properties of SCGs together with the mean attitude scale scores showed variations in the answers (refer Appendix EE). The highest attitude scores were achieved by respondents who stated that they believe in both the performance- and recovery-enhancing properties of SCGs, while the lowest scores were achieved by respondents who stated that they do not believe in either of these properties as can be seen in Appendix EE. This observation was confirmed by a Mann-Whitney test, which revealed a significant difference in attitude scores of respondents who stated that they believe in the performance-enhancing properties of SCGs (*Md* = 43, *n* = 71) and the ones who did not believe in these properties (*Md* = 36, *n* = 74), *U* = 668.500, *z* = -7.758, *p* < 0.001, *r* = 0.64 (effect size *r*: small = 0.01, medium = 0.30, large = 0.50), as well as a significant difference between attitude scores of respondents who believe in the recovery-enhancing properties of SCGs (*Md* = 41, *n* = 113) and the ones who do not believe in these properties (*Md* = 33.5, *n* = 32), *U* = 632.000, *z* = -5.615, *p* < 0.001, *r* = 0.47. The results show that respondents answered questions consistently and reinforce the reliability of the scale.

No significant difference in attitude scores among males (*Md* = 39, *n* = 94) and females (*Md* = 40, *n* = 51, *U* = 2244.5, *p* = 0.527, *r* = 0.05) or age groups (≤40, *Md* = 39, *n* = 64; >40, *Md* = 40, *n* = 81, *U* = 2387.5, *p* = 0.415, *r* = 0.07) could be identified using Mann-Whitney tests. Further, Kruskal-Wallis tests revealed no significant differences between attitude scores across the three different groups of training hours and the six different groups of competition levels. However, Mann-Whitney tests revealed that there was a significant difference in attitude scores between respondents who stated that their SCGs fulfilled their expectations (*Md* = 40, *n* = 136) and the ones who stated the opposite (*Md* = 33, *n* = 9). This result further strengthens the consistency of responses.

6.3.4 Product Preferences

The respondents' expectations were overwhelmingly fulfilled by their SCGs (93.8%), which is also reflected in high levels of satisfaction related to all garment characteristics. No significant associations were found between fulfilled expectations and gender, age, training hours, competition level, or years of experience using chi-square tests for independence. There was a high level of satisfaction among respondents regarding the level of compression and fit of their SCGs with 91% and 87.5% respectively stating that they were 'satisfied' and 'very satisfied' with their current SCGs. The majority (90.3%) was also 'satisfied' or 'very satisfied' with the functionality of their SCGs. The main SCG brands worn by the respondents were Skins (40%), 2XU (26.3%), Under Armour (24.8%) and Nike (20.7%). Skins and 2XU are two of the most established SCG specialists and can be classed as premium brands based on price point (£70+ for long tights), whereas Under Armour and Nike fall into the mid-range category (£35-70 for long tights). Examining the percentages of cases, 96.7% of respondents stated that they wear premium brand SCGs, 85.7% stated that they wear mid-range brand SCGs, whereas 20.8% stated that they wear budget brands, such as retailers' own-brands. Despite the preference for premium and mid-range brands, price was selected as the decisive factor in purchase decisions by 31.7% of respondents (see Figure 6.4). The same percentage of respondents selected fit as the key factor for choosing SCGs. The respondents' preference for premium and mid-range brands is supported by the fact that 17.9% of respondents stated that they base their purchase decisions on brand names. Style, however, is only a secondary factor for the survey respondents when buying SCGs (2.8%). No significant associations were found between the factors influencing purchase decisions and gender, age or weekly training hours using chi-square tests for independence.

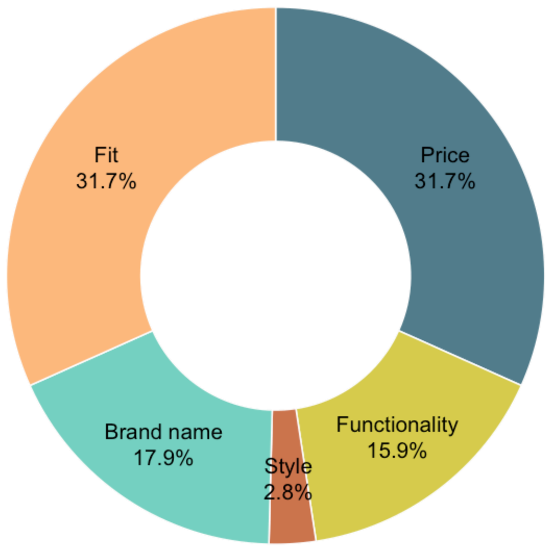


Figure 6.4: Factors influencing SCG purchase decisions of survey respondents (*n* = 145)

23.5% of female respondents stated that they wear SCGs because of their figure enhancing properties, while only 4.3% of men selected this reason. This indicates that women are more concerned about their appearance than men. This assumption is strengthened by the answers of female respondents to the question of how important design/style of SCGs were to them. 83.3% of females stated that the design/style of SCGs was 'somewhat' to 'very important' in contrast to 62.8% of male respondents. As was identified by the survey, most females wear their SCGs as outer layer and hence have higher aesthetic demands on SCGs than men who are more likely to cover them with additional clothing.

The most important garment characteristics for the respondents (*Md* = 1) were comfort, fit, functionality, quality and level of compression. Satisfaction levels of these characteristics were high (*Md* = 1), especially for comfort, fit and functionality, which were 'very important' aspects for 82%, 80% and 72% of respondents, respectively. This reflects the high level of fulfilled expectations of the respondents (93.8%). Garment characteristics with the least importance to the respondents (*Md* = 3) were soft hand and UV protection.

The respondents were asked what features they would like in their SCGs that are currently not available on the market. 74 out of the 145 respondents did not comment or stated that they do not require any improvements. Comments from the remaining respondents were grouped according to themes as shown in Table 6.2. Most comments (*n* = 15) were related to size and fit, in particular in relation to size options for taller wearers and generally a wider size range as well as better fit. The second most frequently mentioned feature that respondents would like to see on their SCGs was pockets. Due to the skin-tight fit of the garments, SCGs are mostly not fitted with pockets. However, since almost half (49%) of all respondents and 76.5% of female respondents treat SCGs as outerwear, this is an important design feature to consider. A few respondents stated that the prices of SCGs were too high (*n* = 7) and that they wished the quality and durability of the garments would be improved (*n* = 6).

Table 6.2: Garment Improvements suggested by survey respondents (*n* = 71)

Garment improvements	*n*
Improved size and fit	15
Pockets on garments	11
Lower price	7
Better quality/durability	6
Specific garment designs	6
Easy care properties	4
Material-related improvements	4
Improved design/style/colour	3
Easier donning/doffing	3
Improved thermal regulation	3
Targeted compression	2

Garment improvements	*n*
Other/ungrouped	7

6.4 Discussion of Findings from Study 1

Interestingly, the majority of respondents believe in recovery-related benefits of SCGs, whilst only about half believe in performance-related benefits. It was also stated by 22% of non-SCG users that they do not wear SCGs because they do not believe in their performance-enhancing properties. In addition, a number of respondents commented that they would like to see scientific evidence that SCGs work. As was suggested by Brophy-Williams et al. (2015), it could be possible that performance-improving properties of SCGs have not been present for some of the respondents because the level of pressure was not sufficient due to problems with sizing and fit that affect compression. The findings also show that SCGs are mainly worn for recovery reasons and injury prevention. More than half of respondents (57.2%) wear SCGs to prevent injuries even though brands primarily advertise SCGs as making wearers “train harder, perform longer and recover faster” (Skins, 2016) and not necessarily for injury prevention.

Despite the relatively low belief in the performance-enhancing effects of SCGs, the overall attitude towards SCGs by survey respondents was positive and they were overly satisfied with their commercial SCGs. The vast majority stated that their SCGs fulfilled their expectations. This indicates that they are likely to continue to wear SCGs, meaning that there is a continued demand for SCGs. This observation goes in line with market reports that forecast continued growth of the SCG market (Fiedler, 2015). With continued SCG use and expansion of the SCG market, users are likely to develop more technical knowledge and with this might develop higher standards on SCGs in terms of functionality, fit, comfort and style. Hence, research supporting the design of SCGs is warranted.

Overall, three themes emerged that are critical to SCG users, listed in decreasing order of importance: physiological effects of SCGs, the feeling whilst wearing SCGs and elements related to aesthetics. Aesthetics are of more importance to female respondents than males. This finding goes in line with the findings of a Mintel (2015b) survey, which reported that women have a higher interest than men in sportswear that is not just comfortable, but also the latest fashion. Women are also often more concerned about their body image than men (refer section 3.2.3). As a consequence, they are more interested in the figure-enhancing properties of SCGs.

Whilst there were no differences in attitudes towards SCGs among female and male survey respondents, there were differences in the wear habits of females and males. The majority of female respondents tend to wear SCGs as outer layer, whilst men prefer to wear them as base layer. Whether SCGs are treated as base layer or outer layer has implications on many garment aspects, such as fabric choice, thermal properties, durability and style. Women, for instance, want the garments to be aesthetically pleasing and have the functional properties of an outer garment (e.g. pockets).

Comfort, fit and functionality are characteristics of SCGs that are among the most important to the survey respondents and with which they are overwhelmingly satisfied. When it comes to purchase decisions, price and fit are the predominant influential factors. Fit is one of the most important concerns, which is not surprising since it is critical for adequate pressure application. However, with many sizing systems of SCGs being based on the Body Mass Index (BMI) (ratio of height and weight) rather than circumferences, there are likely variations in pressure levels across different individuals. It is important to consider that the survey respondents are recreational athletes and, thus, do not possess the technical knowledge that elite athletes would. Fit and pressure levels of commercial SCGs are reported in the wearer trials (Chapter 8).

6.5 Chapter Conclusions

This chapter presented the findings of an online survey with 145 SCG users providing insights into the untouched field of user experiences with SCGs. The survey respondents, who mainly used premium and mid-range brand SCGs, were overly satisfied with their commercial SCGs and used their SCGs mainly to enhance recovery and prevent injuries rather than increasing performance. This was reflected in their beliefs as a larger proportion of survey respondents believed in recovery benefits than performance benefits of SCGs.

The findings highlighted differences in the way males and females use SCGs with women treating SCGs as outer layer and having higher aesthetic demands than men. The design of SCGs requires considerations of garment functionality, the feeling of wearing the garments (e.g. thermal and psychological comfort) as well as aesthetics of the garments.

There are no published studies on consumers’ perspectives of SCGs. Because this research project applied a user-centred research approach, it was essential to have user information to feed into the subsequent studies. The findings about popular SCGs among survey respondents led to the selection of women’s SCG type and brand for the subsequent studies, increasing the relevance of the study.

7 FINDINGS FROM PHASE II – STUDY 2: COMMERCIAL SPORTS COMPRESSION GARMENTS

7.1 Chapter Introduction

Study 2 focused on analysing commercial sports compression garments (SCGs) for female athletes with particular focus on the design, materials, sizing and applied pressure, addressing Aim 3 of this research project. The garments under investigation were the Skins A400 Women's Active Long Tights (article no. B33001001) and the Skins A400 Women's Active Long Sleeve Top (article no. B33001005) in sizes Small, Medium and Large (refer Appendix L). The following sections describe the results of the fabric analysis, garment analysis and the size chart review, which all form part of Study 2. The insights from Study 2 were needed to better understand the behaviour of the SCGs on the human body in the subsequent wearer trials (WTs) and for the evaluation of virtual fit for pressure prediction.

7.2 Fabric Analysis

One set of the long sleeve compression top and long compression tights under investigation were deconstructed for the fabric analysis.

7.2.1 Objectives of Fabric Analysis

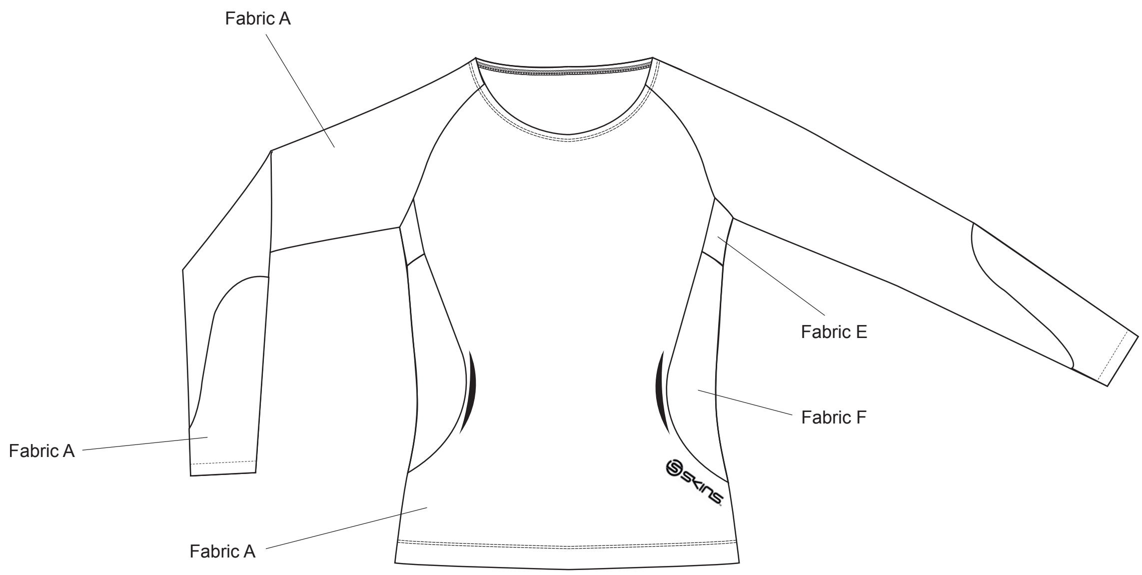
The objectives of the fabric analysis were threefold:

1. To identify the key properties of the fabrics used in the Skins A400 compression top and tights.
2. To compare fabric properties of the Skins A400 compression garments to other fabrics used for compression sportswear.
3. To identify properties required for simulation.

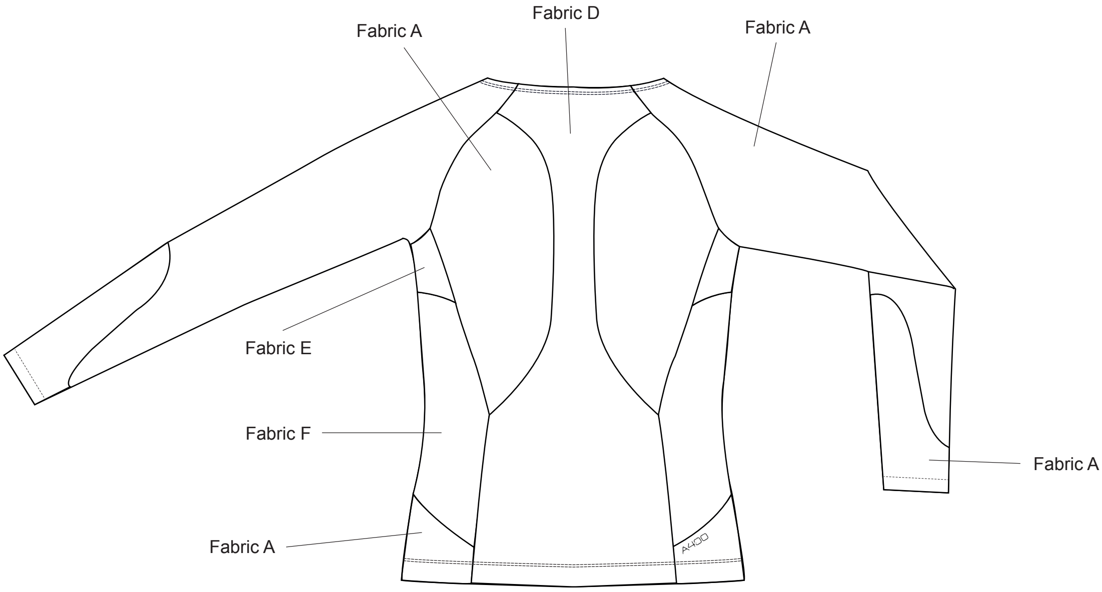
7.2.2 Findings of Fabric Analysis

The six different fabrics (Fabric A, B, C, D, E and F) used in the Skins compression top and tights were analysed alongside four fabrics (Fabric P1, P2, P3 and P4) used for SCGs provided by a start-up brand. The results from the fabric tests are presented in Appendix FF.

As can be seen in Figure 7.1 and Figure 7.2, Fabric A was the main fabric used in both the compression tights and top, whilst the other fabrics were only used for smaller panels across the body. Fabrics B and C were only used in the compression tights. Fabric C was used for the waistband pocket and in combination with Fabric D on the side of the upper thigh (over the tensor fasciae latae (TFL) muscle and iliotibial band (ITB)), whilst Fabric B was used on the waistband. Fabric F was only used in the compression top on the waist.

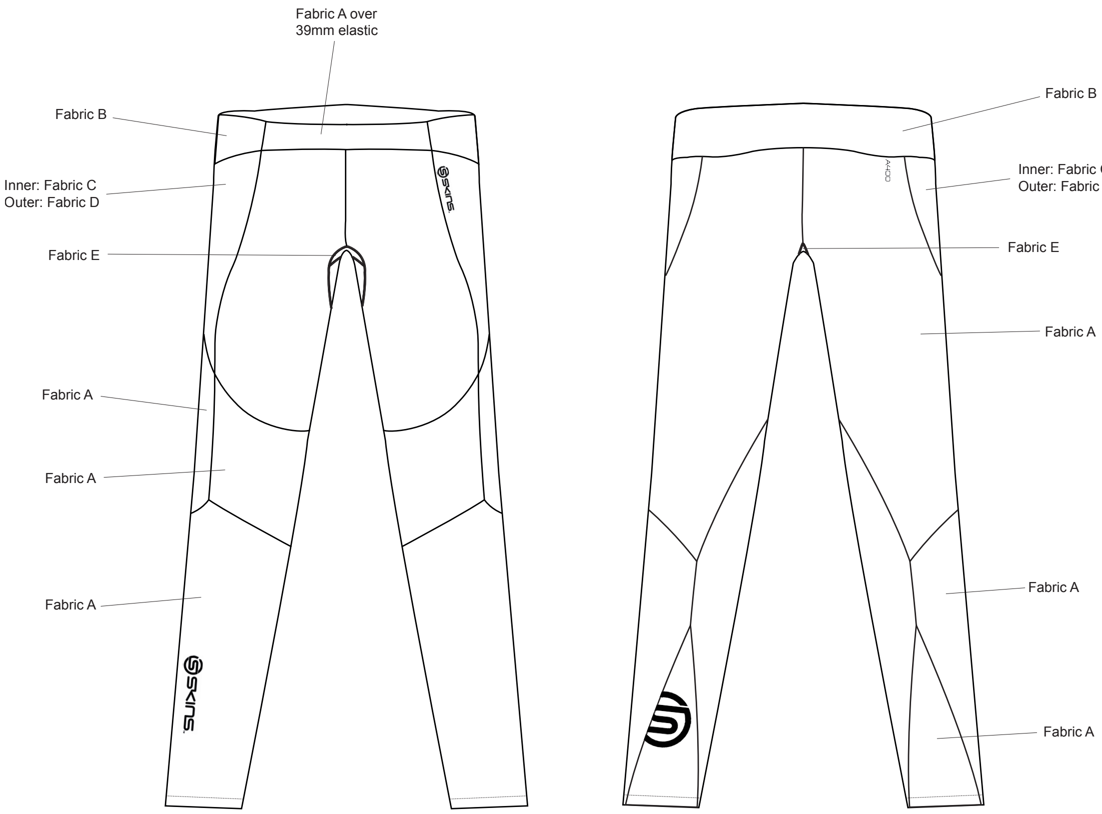


a)



b)

Figure 7.1: Use of different fabrics in compression top: a) front view; b) back view



a) b)

Figure 7.2: Use of different fabrics in compression tights: a) front view; b) back view

The care labels of the Skins compression top and tights stated that the fabrics were made from 76% nylon/polyamide and 24% elastane. Fabrics P1 and P2 also contained nylon and elastane, in contrast to Fabrics P3 and P4, which contained polyester and elastane fibres. The elastane content was 18% for Fabrics P1, P3 and P4 and 23% for Fabric P2.

Higher amounts of elastane reduce a fabric’s strength, whilst increasing its stretch properties. The fabrics provided by the start-up brand featured slightly lower elastane contents than the Skins fabrics. However, it needs to be considered that fabrics are complicated structures and that the physical properties that can influence compression, depend on the mechanical properties of the fibres (e.g. fibre cross section) and yarns (e.g. yarn count) used to knit the fabrics, as well as the construction of the fabric.

All fabric structures were warp knits as was identified by microscopic analysis (refer Appendix Figure FF-1 to Appendix Figure FF-3). Fabric E, used as ventilation panel in the underarm area of the top and the crotch area of the tights, was a warp knitted mesh. Fabric C was a lighter warp knit structure with a shiny appearance and a soft hand, constructed from very fine yarns. It was used for the waistband pocket and as an inner layer at the side thigh panel facing Fabric D. The knit structures of Fabrics B and D were analysed in more detail as the fabrics had interesting surface structures. Fabric B, which was used at the waistband, appeared heavier and had a rougher hand compared to the other materials and featured high stretch in crosswise (course) direction only. A closer look at the fabric structure in stretched condition revealed that the knit structure was a sharkskin structure.

Fabric D was also a one-way stretch knit. The technical face of Fabric D was shiny, whilst the technical back showed slightly raised ridges. These ridges were caused by a weft insertion. The fabric featured a 1x1 tricot warp stitch with inserted yarn. The weft-inserted yarn was clearly visible in the enlarged view of Fabric D in stretched condition. The yarn insertion and resultant fabric ridges are likely supporting the moisture wicking process. Fabric D was used at the centre back, an area of the body with high sweat levels (refer Appendix Figure A-6). The inserted yarn added the high stretch level in crosswise direction due to high elastane content of the yarn.

The microscopic images of the technical backs of Fabrics P1 and P2 showed that they had brushed surfaces, which tend to be softer next to skin. Compared to weft knit structures, the loop formation of warp knit structures provides less inherent fabric stretch (Cohen et al., 2012). Stretch is added through the inclusion of elastane fibres in the knitting yarns. This allows more control over the fabric stretch behaviour compared to knit structures with high levels of inherent stretch.

The key fabric properties (refer Appendix Table FF-1) of the different fabrics differed substantially due to the different fabric structures. Fabrics B and D had the highest weight and bulk density of all analysed fabrics. Fabric A was the main fabric used in the Skins A400 SCGs and referred to as ‘Memory MX’ fabric by the brand. It had a notably lower bulk density, but higher stitch density, indicating the use of very fine yarn for Fabric A. The Skins website (2016) stated that Fabric A was 70 Denier, whilst Fabric D was 210 Denier. The website did not state any information about the other fabrics used.

One of the key properties for fabrics used in compression sportswear is their ability to extend and recover to their original shape after extension. Stretch and recovery tests (BS 4294:1968) were, therefore, conducted. Due to limited sample availability, not all fabrics could be tested in both course (crosswise) and wale (lengthwise) directions (refer Appendix Table FF-2). Fabric D had the highest extension rate in course direction of the fabrics tested (228.29%) and the lowest extension in wale direction (73.03%). Fabric D was used in the centre back of the compression top and in combination with Fabric C on the upper thigh of the compression tights. Higher extension rates in crosswise direction allow the SCGs to expand around the circumference of the body. Fabric B, which was used for the waistband of the compression tights, had the lowest level of course extension (105.76%). The use of a fabric that is less easily stretched at the waistband means that the wearer’s midsection is pulled in more by the garment.

There was a 13.55% residual extension after 30 minutes of relaxation in course direction of Fabric A. This means that Fabric A does not fully recover to its original size after extension in crosswise direction. Since Fabric A is the main fabric of the compression tights and top, compression levels applied to the wearer’s body are likely to decrease over time as the garment would not return to its original shape after being stretched during wear. The extension rate of Fabric A in wale direction was substantially lower than in course direction. This is a common characteristic of tricot-warp knits (Kadolph, 2014). Fabric A recovered better in wale direction with a residual extension of less than 2% after 30 minutes. The wale direction of Fabric A runs vertically along the compression top and tights with the exception of the knee panel. The width of the garment, thus, expands more than the length of the garment, whilst the knee panel of the tights provides more stretch in lengthwise direction. The garment has likely been designed this way to accommodate bending of the knee joint. The poor recovery properties in course direction stand in harsh opposition to the claims made on the Skins website that their ‘Memory MX’ fabric (= Fabric A) “returns to its original shape no matter how much stress you put it under” (Skins, 2016).

Compared to the Skins fabrics, the fabrics provided by the start-up brand had a higher extensibility, but did not fully recover after extension either. The recovery rates of all fabrics provided by the start-up brand were generally poorer than the recovery rates of the Skins fabrics, indicating potential problems with maintaining compression levels over time. However, a comparison is difficult due to the limited data obtained for the Skins fabrics.

Conventional stretch fabrics are generally expected to recover from about 25% extension, whilst power stretch fabrics are expected to recovery from 200% (Taylor, 1990). Residual extension of up to 3% is generally acceptable (Saville, 1999). The results obtained by Allsop (2012) from the stretch and recovery analysis of fabrics used in compression tops (following the same test standard) were much closer to this benchmark for course direction than the fabrics analysed in this study with stretch and recovery values within 95-96%.

Despite having the highest elastane content of the four fabrics from the start-up brand, Fabric P2 had the lowest level of extension. Generally, higher elastane contents relate to higher extensibility. However, Fabric P2 had a lower stitch density than the other fabrics, which would affect the mechanical extensibility of the fabric. Fabric properties are complex and intertwined and, thus, their behaviour is difficult to predict.

Bursting strength tests (BS EN ISO 13938-2:1999) were conducted for Fabrics A, P1, P2, P3 and P4 only as there were no samples of sufficient size available from the other fabrics. None of the fabrics ruptured during the test (see Appendix Table FF-3), which can be attributed to the high elastane content of the fabrics.

To further investigate the elastic behaviour of Fabric A, a stress-strain curve was produced as presented in Figure 7.3. The curve of Fabric A in crosswise direction indicates that the fabric has desirable elastic properties for SCGs. Variations in fabric stretch around the body circumference should not result in substantial pressure variations based on the flat stress-strain curve. However, as discussed, pressure application is also influenced by numerous other aspects, so inter-individual pressure variations could still occur.

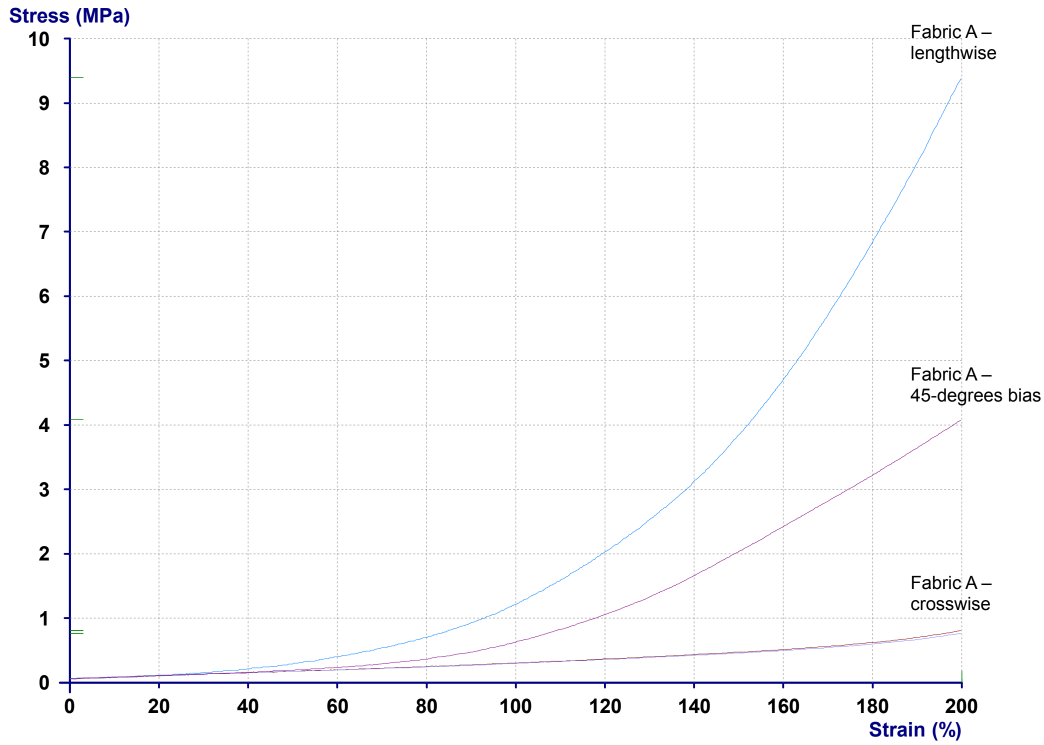


Figure 7.3: Stress-strain curve of Fabric A in wale-, course- and bias-direction

Moisture management properties of fabrics are important aspects of comfort during wear. The moisture management performance of the different fabrics under investigation with exception of Fabrics B, C, E and F was assessed using the Moisture Management Tester (AATCC 195:2009) (see Appendix Table FF-4). All fabrics were classed as ‘water penetration fabrics’ by the testing system. This means that the fabrics feature excellent one-way water transport and only little spreading of water on the fabric surface (Yao et al., 2006). The overall grade for moisture management properties of the fabrics showed slight variations with Fabric A and D having slightly better grades than the fabrics provided by the start-up company. This could potentially be accredited to the ADAPTIVE (HeiQ

Materials AG, Schlieren, Switzerland) fabric treatment that is used on the Skins fabrics. ADAPTIVE is a fabric finish that adjusts the rate of cooling and evaporation of perspiration according to the body temperature. The technology is based on hydrofunctional polymers, which cover the fibres in a fabric. The polymers bind moisture in their structure at low temperatures to keep the wearer warm and dry and release the stored moisture to the surface at warm temperatures, so that it can evaporate and cool the fabric and the wearer's skin (Bekaert Deslee, 2016). Fabric finishes add another layer of complexity to fabric properties and the prediction of their behaviour.

In addition to the above tests, FAST-1 and FAST-2 tests of the SiroFAST system were conducted (see Appendix Table FF-5). These measurements were thought to be required for the realistic simulation of fabrics in Phase III in combination with the area density and stretch measurements of the fabrics. The FAST-3 extension test was also carried out, but most measurements reached the maximum measuring capacity of the FAST extension meter, which was originally designed to measure stretch behaviour of woven wool tailoring fabrics.

It is important to consider bending characteristics when examining the fabric-body-interactions. A higher level of bending rigidity means a fabric conforms less easily to the contour of the body (Emirhanova and Kavusturan, 2008). Fabric weight can affect bending rigidity (Venkatraman, 2015). There was a wide variety of weights across the different fabrics analysed ranging from 111g/m^2 (*SD* ±3.83) (Fabric C) to 320.8g/m^2 (*SD* ±3.35) (Fabric B). Fabric A, the main fabric used in the SCGs, had a medium weight (206.4g/cm^2) compared to the other fabrics used. Thickness of a fabric depends on the bulk density of the yarns and fabric construction (Taylor, 1990) and can affect fabric stiffness. Fabric thickness also has a major effect on thermal resistance. Most fabrics analysed in this study, with exception of Fabric C, would be classed as thick fabrics (Venkatraman, 2015). The thickness of Fabric A (0.66mm) was one of the highest alongside Fabric B. Nevertheless, the bulk density of Fabric A was the second lowest, namely 0.31g/cm^3. Fabric A also had a considerably higher stitch density than the other fabrics. This means that the knit has a tighter structure and used finer yarns.

This analysis only focused on key fabric properties, as the objective was to get an understanding of the main parameters that characterise fabrics and that are required for 3D simulation. Compression is also influenced by the yarn properties (e.g. yarn count, twist) (refer Alisauskiene and Mikucioniene, 2014; R. Liu et al., 2017), which is beyond the scope of this study. The findings of this study showed that it is important to consider that two different SCGs that appear to be similar, can vary widely in fabric properties and consequently compression levels. However, due to the complicated structures of fabrics and their fibre, yarn and construction properties, it is not yet understood how specific variations in fabric properties translate into pressure variations.

7.3 Garment Analysis

The Skins A400 compression top and tights in sizes Small, Medium and Large were analysed as a whole.

7.3.1 Objectives of Garment Analysis

The objectives of the garment analysis were:

1. To re-engineer the Skins A400 compression top and tights and obtain relevant garment design specifications.
2. To obtain pressure values applied to mannequins.

7.3.2 Findings of Garment Analysis

7.3.2.1 Garment Design and Construction

The results of the analysis of garment design and construction of the SCGs under investigation are presented in Appendix GG.

The Skins A400 women's SCGs featured a plain-coloured, black design with subtle reflective graphics that appeared gold-coloured in bright light conditions (refer Appendix Figure GG-1). They had a relatively simple design on first sight, but panelling and seam positioning of the garment were complex. According to Skins (2016) the design is based on supporting key muscle groups as described below:

> "SKINS have a unique way of wrapping and supporting your key muscle groups to reduce movement and focus direction. The seams on SKINS are strategically placed to act as 'anchor points' offering focused support and stability and promoting a heightened sense of proprioception."

The compression top was constructed from twelve fabric panels with five panels being mirrored/paired panels, whilst the compression tights consisted of 23 fabric panels, nine of which were mirrored/paired panels. The waistband featured a strong elastic webbing covered by Fabric A at the front of the compression tights and a different, less elastic fabric (Fabric B) at the sides and back (see Appendix Figure GG-2). The compression top featured a piece of elastic webbing with silicone anti-slip coating (see Appendix Figure GG-3). Two layers of fabric were used on the upper outer thigh as well as in the crotch area. Bills of Materials (BOM) indicating the different panels, fabrics and components used in the garments were created (see Appendix Table GG-1 and Appendix Table GG-2).

Due to the large number of fabric panels, it was important to analyse the garment construction methods used to join the panels. The different panels were joined using flat seam stitches with 'A-seams' (see Figure 7.4) being the predominantly used seam type. These non-standardised cover-type seams were especially developed for performance sportswear to improve comfort and reduce chafing. Unlike standard class 600 sitches, where the edges of the two fabrics to be joined are butted together, the fabric edges overlap slightly in 'A-seams' as shown in the cross-sectional view in Figure 7.5.

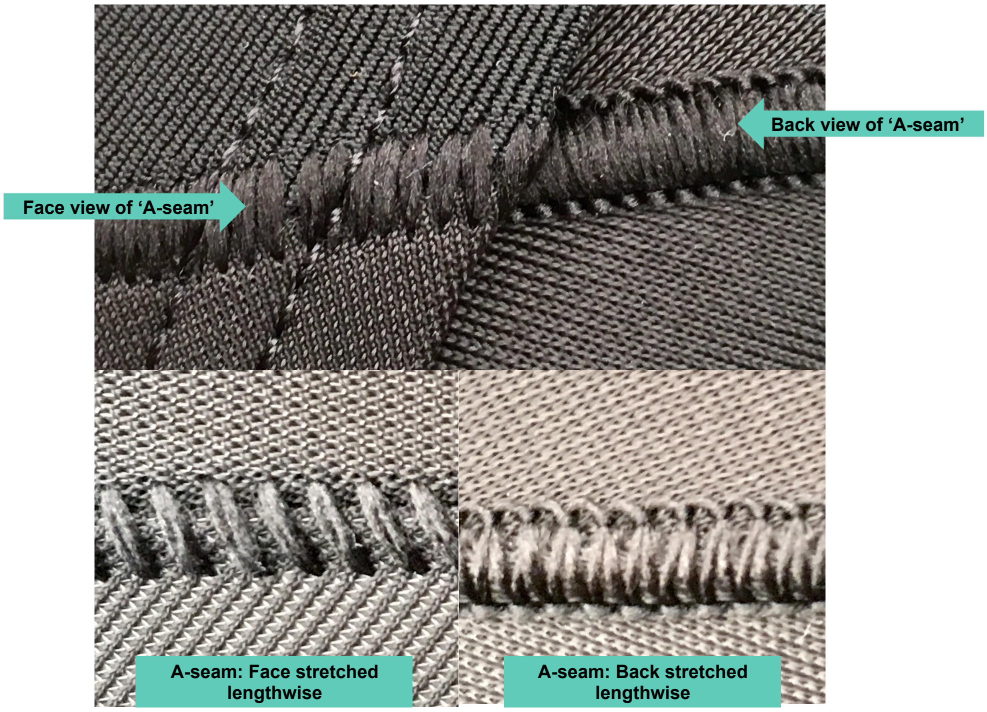


Figure 7.4: Face and reverse views of 'A-seams' on the SCGs

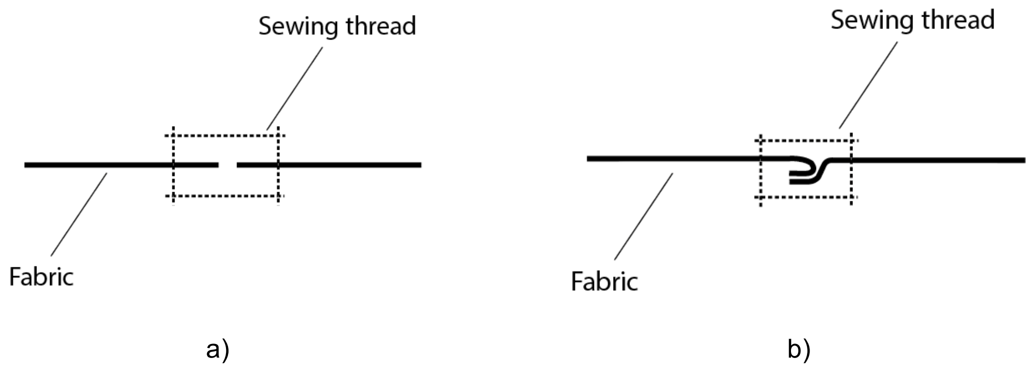


Figure 7.5: Simplified cross-sectional view of conventional cover seam with butted fabric edges (a) and 'A-seam' with overlapping fabric edges (b)

The ISO 607 wide cover stitch, used for the inseam and crotch area of the compression tights, is frequently used in elastic sportswear, as it is a flat seam eliminating chafing and ensuring extensibility along the length of the seam (McLoughlin and Hayes, 2015). The ISO 406 twin needle bottom cover stitch, which is used on the waistband and on the neck and bodice hems, provides good extensibility whilst being stronger than lock stitches (Carr et al., 2008; Bubonia, 2014; McLoughlin and Hayes, 2015), which is important for compression sportswear.

Skins (2016) claim that the 'A-seams' used throughout the compression top and tights are 30% stronger than standard stitches. Additional strength could potentially come from the overlapping of fabrics. It is noteworthy that the slightly overlapped fabrics are on the inside of the garments, which could potentially cause discomfort. However, the seam is constructed with a soft bulk thread, which is likely to improve tactile comfort. Since SCGs are stretched extensively and have to withstand a lot of force from stretching, stronger seams are a preferred choice over conventional flat seams. However, the use of a bulk cover thread on the outside of the garment could potentially mean that the seam is not as resistant to abrasion as flat seams using twisted yarns. This could be the reason why an ISO 607 cover stitch instead of an 'A-seam' was used for the inseam, crotch and back rise seams, as these areas would be exposed to extensive abrasion by rubbing against each other or to other surfaces during exercise.

The cuffs at the sleeves and legs were bonded. According to Skins this was done for optimised compression and increased comfort. The cuff joining seams at the sleeves and legs were reinforced with bar tacks. A summary of the stitch and seam types used for the compression top and tights is listed in Table 7.1.

Table 7.1: Summary of stitch and seam types used in Skins A400 SCGs

		Stitch Types	Seam Types
Top	Joining panels	Non-standard cover stitch	Flat seam: A-seam
	Hem	ISO 406 twin needle bottom cover stitch	Edge finishing
	Neck opening	ISO 503 over edge, 406 twin needle bottom cover stitch	Edge finishing
	Sleeve opening	Bonded, not sewn	Edge finishing
Tights	Joining panels	Non-standard cover stitch	Flat seam: A-seam
	Inseams	ISO 607 wide cover stitch	Flat seam
	Waistband	ISO 503 over edge, 406 twin needle bottom cover stitch	Superimposed seams
	Leg opening	Bonded, not sewn	Edge finishing

The positioning of the different seams is highlighted in Figure 7.6 and Figure 7.7. Both garments do not have any side seams. The seams of the compression top are placed near the oblique muscles and about a quarter width away from the sides of the tops, enabling the use of different fabrics for the waist and underarm sections of the top. Seam positioning also separates out the shoulder blades at the back of the top. The seam positioning of the compression tights is also based on separating different muscle groups, such as the TFL muscle and ITB at the upper thigh and the Achilles tendon.

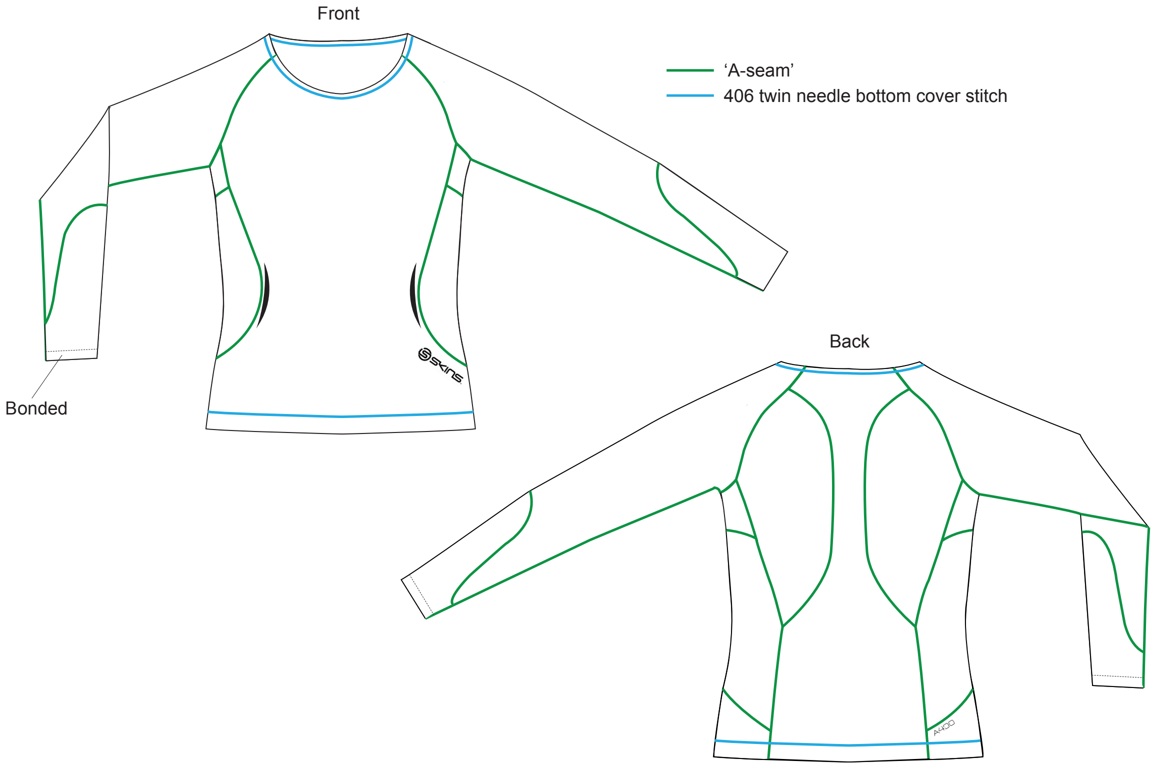


Figure 7.6: Seam positioning of compression top

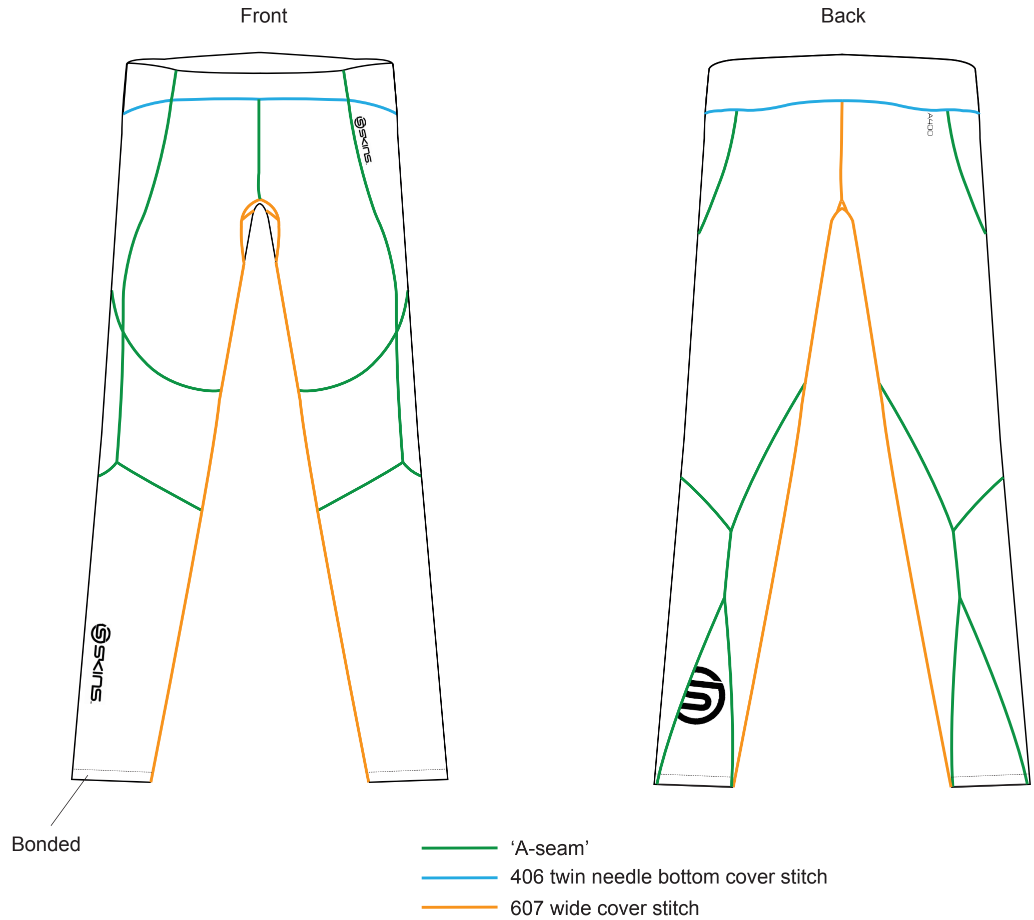


Figure 7.7: Seam positioning of compression tights

7.3.2.2 Garment Patterns and Grading

The garment patterns of the Skins SCGs were re-created by digitising the panels of the deconstructed SCGs. The re-engineered patterns are presented in Figure 7.8 and Figure 7.9. The pattern of the compression top consisted of a raglan sleeve with separate cuff, a front and a back panel with separate panels for the waist and shoulder blades and a small underarm panel to allow the use of a mesh fabric for ventilation. The design of the compression top followed a body map approach. The isolation of certain torso areas through separate pattern panels allows the use of different fabrics to match distinctive requirements. The pattern of the compression tights followed a similar approach with, for example, the knee panel being isolated to improve freedom of movement.

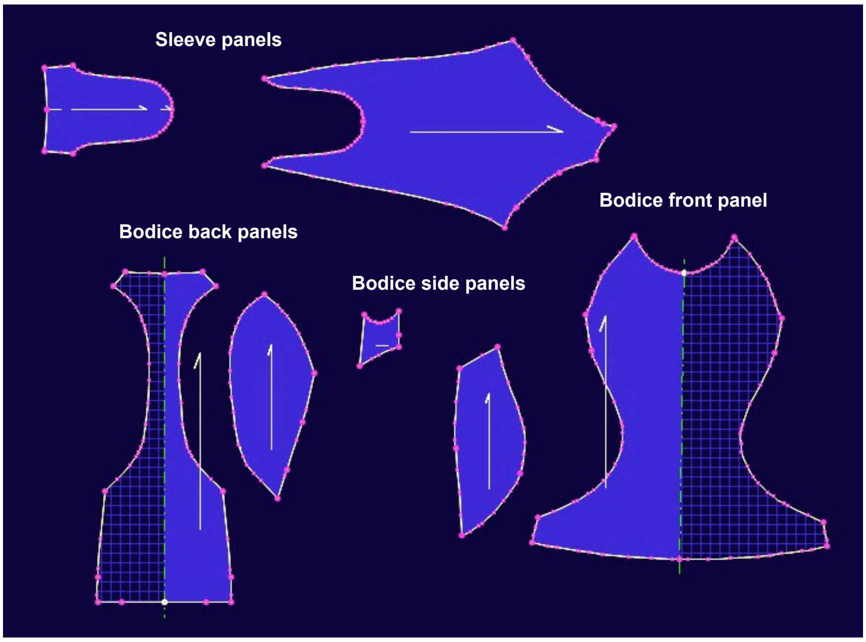


Figure 7.8: Re-engineered pattern of compression top (screenshot)

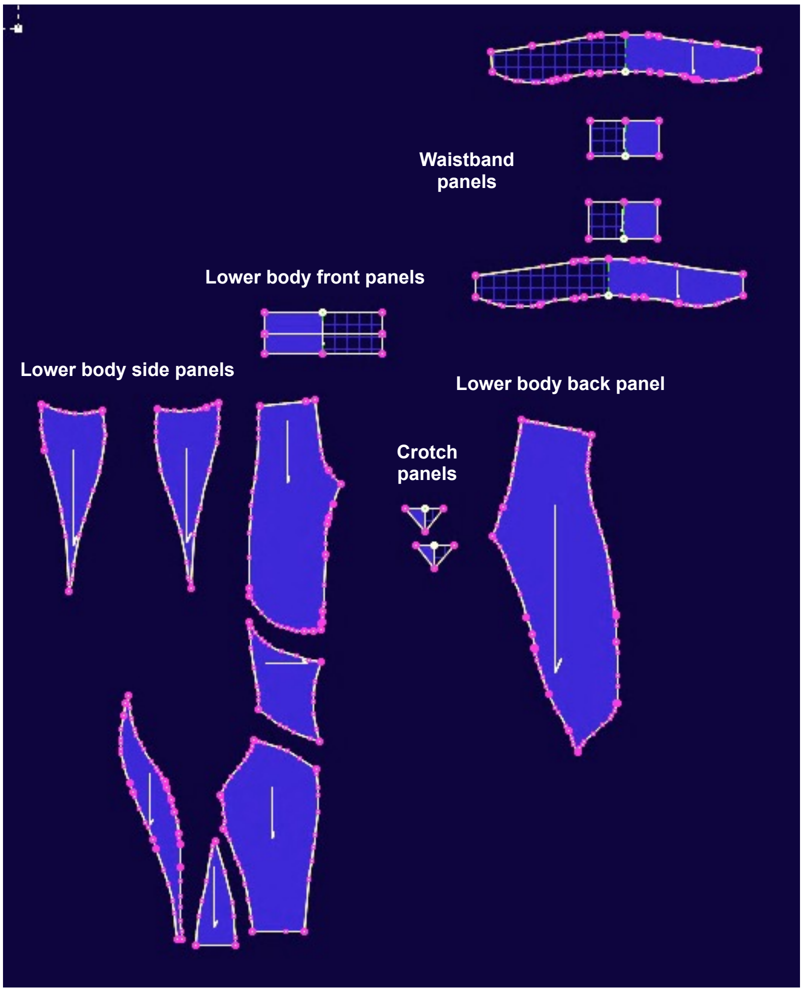


Figure 7.9: Re-engineered pattern of compression tights (screenshot)

The different sized SCGs under investigation were measured at key measurement locations across the garment (refer Appendix Table GG-3 and Appendix Table GG-4). The differences between the garment flat measurements in sizes Small and Medium as well as Medium and Large were calculated as shown in Table 7.2 and Table 7.3. The results were translated into total grade increments applied to the garment patterns as presented in Table 7.4 and Table 7.5. Some of the grades were slightly adjusted due to tolerances in the garment flat measurements. A combination of equal and variable grades was used in both SCGs.

Table 7.2: Grade increments for compression top based on garment flat measurements

	Top - Point of Measure	S-M Grade Increment	M-L Grade Increment
1	Front length (side neck point to hem)	0.9	0.8
2	Centre back length	1.3	1.2
3	Side length	0.6	-0.6
4	Chest width (2.5cm down from underarm)	1.8	3.1

	Top - Point of Measure	S-M Grade Increment	M-L Grade Increment
5	Across chest (6.5cm down from centre neck seam)	1.8	1.4
6	Across back (10cm down from centre neck seam)	0.5	1.4
7	Waist width (40cm down from shoulder high point)	1.6	2.8
8	Bottom opening width (edge to edge, straight)	1.8	2.6
9	Sleeve length top armhole (shoulder high point to sleeve opening)	0.9	1.7
10	Sleeve length underarm	0.5	0.9
11	Curved armhole width	1.7	1.7
12	Sleeve width (2.5cm below armhole, parallel to sleeve opening)	1.1	1.0
13	Elbow width (1/2 of underarm sleeve length)	1.0	0.7
14	Sleeve opening width	0.5	0.4
15	Neck depth front	0.2	-0.1
16	Neck drop front	0	0.2
17	Neck drop back	0.1	0.3
18	Neck width	0.7	0.7
19	Neck base	0.7	0.6

Table 7.3: Grade increments for compression tights based on garment flat measurements

	Tights - Point of Measure	S-M Grade Increment	M-L Grade Increment
1	Waistband depth CF	0	0.1
2	Waistband depth CB	0.1	0.1
3	Waistband depth side	0.1	0
4	Waistband width front (measured straight at top edge)	3.3	3.2
5	Hip width (10cm down from top edge)	3.8	3.2
6	Inseam (measured along seam, CF seam to hem)	0.4	0.3
7	Outseam/length (top edge to hem)	2.3	2.0
8	Front rise (top edge to crotch seam intersection, measured along curve)	1.9	1.9
9	Back rise (top edge to front seam, measured along curve)	0.6	2.1
10	Thigh width (5cm down from crotch)	1.5	1.6
11	Knee width (½ of inseam length)	0.8	0.7
12	Calf width (25cm up from bottom hem)	0.9	0.8
13	Leg opening width (measured straight)	0.4	0.2

Table 7.4: Actual grade increments applied to the compression top pattern

Top - Point of Measure	S-M Total Grade Increment	M-L Total Grade Increment
Chest circumference	3.6	6.2
Waist circumference	3.2	5.6

Top - Point of Measure	S-M Total Grade Increment	M-L Total Grade Increment
Hem circumference	3.6	5.2
Curved armhole width front	1.7	1.7
Neck width	0.7	0.7
Biceps circumference	2	2
Elbow circumference	2	1.4
Sleeve opening circumference	1	1
Torso length	1	1
Sleeve length - top	0.9	1.7
Sleeve length - underarm	0.5	1

Table 7.5: Actual grade increments applied to the compression tights pattern

Tights - Point of Measure	S-M Total Grade Increment	M-L Total Grade Increment
Waist circumference	6.5	6.5
Hip circumference	7.6	6.4
Thigh circumference	3	3
Knee circumference	1.5	1.5
Calf circumference	1.6	1.6
Ankle circumference	0.6	0.6
Front rise	2	2
Back rise	0.6	2
Crotch length	2	2.8
Seat length	1.2	1.2
Inseam	0.4	0.4
Side length	2	2

Conventional grade increments for major girths used in industry are generally 4cm or 5cm in Europe and incremental from 1" to 2" in the USA, whilst height grades are generally based on 2.4cm or 0.5” per size (Shoben and Taylor, 2004; Gribbin, 2014). Measurements with equal grades are commonly used for length measurements in garment manufacturing, whereas variable grades are often applied to width measurements increasing in value from smaller to larger sizes (Mullet, 2015). Grading of SCGs is, however, slightly more complex due to the skin-tight nature of the garments and the need to keep compression levels constant across different sizes. The SCGs under investigation had numerous different panels, especially at the lower legs of the tights. Most grades of the tights were equal grades with the exception of the back rise and crotch length. The hip circumference was the only circumference girth of the tights with a decreasing variable grade. The torso circumference grades of the top featured variable grades with substantially higher increments between sizes Medium and Large. The sleeves were graded with a variable grade in length and equal grade for the biceps and sleeve opening widths. However, the elbow featured a decreasing variable grade. Garment elements that were not graded were the waistband depth on the tights and the neck depth and drop of the top. The variations in grading between the compression tights and top are likely linked to the different sizing systems applied. The sizing system for the compression top was based on chest circumference measurements, whilst the sizing system for the compression tights was based on the ratio of height and weight, where, as it appears, an increase in BMI was associated with an equal increase in circumference measurements with exception of the hip circumference.

The identified grading was applied to the patterns in AccuMark® (Gerber Solutions, USA). The final nested grades for the compression top and tights patterns imported into Optitex are shown in Figure 7.10 and Figure 7.11, respectively.

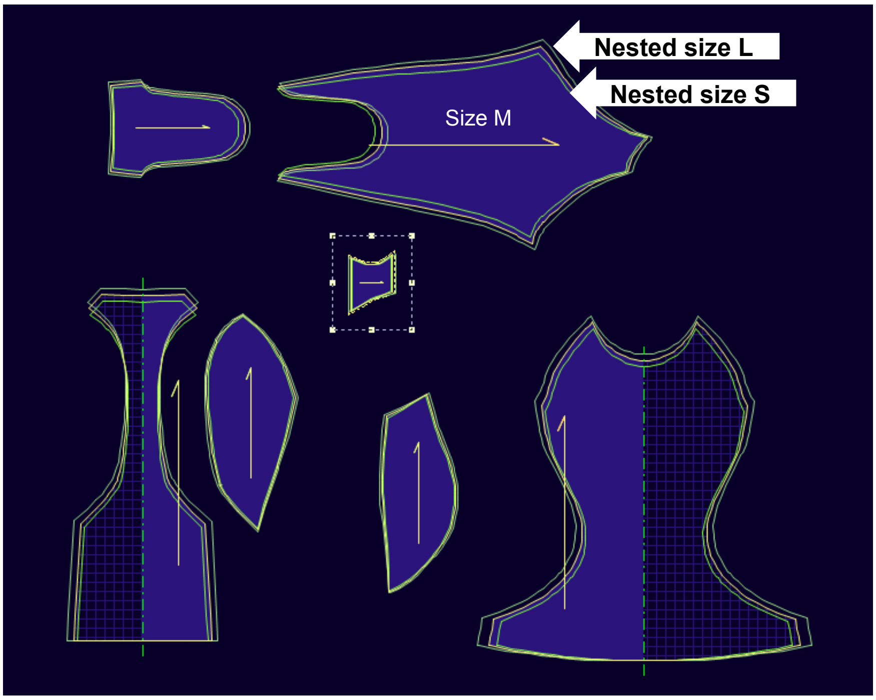


Figure 7.10: Nested grades of compression top pattern (screenshot)

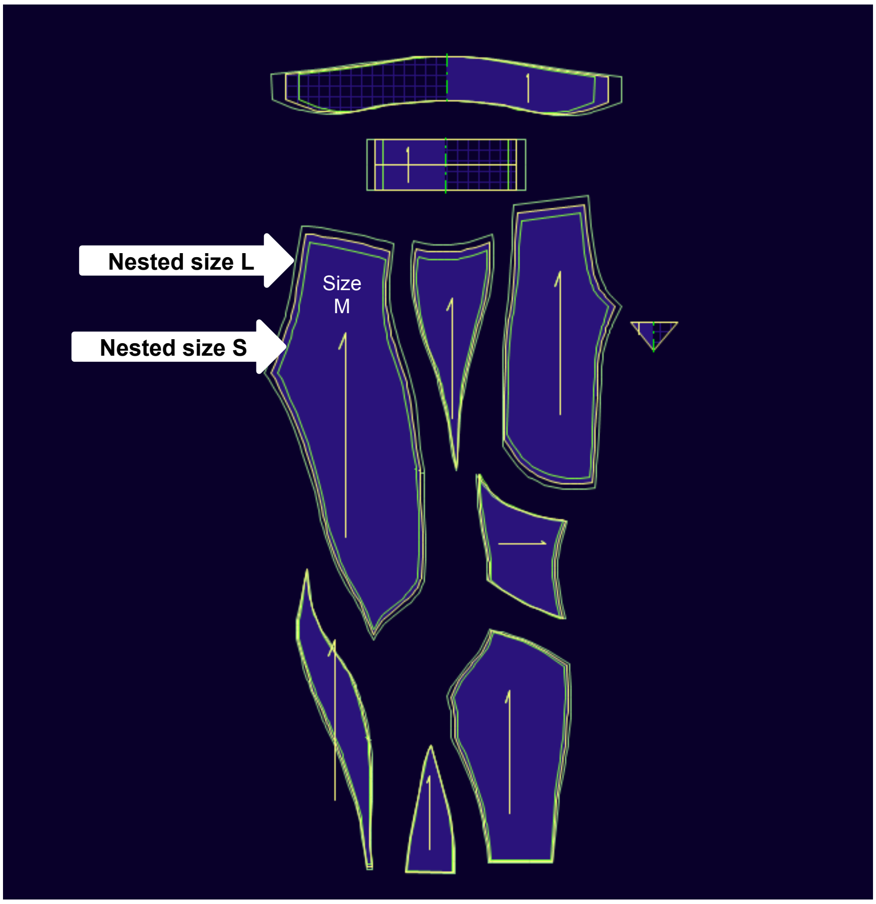


Figure 7.11: Nested grades of compression tights pattern (screenshot)

7.3.2.3 Pressure Measurements on Mannequin

The pressure applied by the Skins A400 Women's Active Long Sleeve Top and Women's Active Long Tights were measured on a mannequin to get an initial idea of the compression behaviour.

Pilot Study

To assess the reliability of the pressure measurement (PM) method, pressure levels were measured on two different mannequins at two different occasions as reported in Table 7.6. No statistically significant differences were detected between pressure values measured on the SCGs worn by mannequin A and mannequin B using Wilcoxon signed rank tests.

Table 7.6: Pressure measurements on two different mannequins of the same body dimensions and composition

	Point of Measure	Mannequin A; tights and top size M	Mannequin B; tights and top size M
Tights	B1	18	16
	B2	16	14
	B3	9	11
	B4	10	11
	B5	10	8
	B6	9	11
	B7	7	6
	B8	3	3
	B9	13	8
Top	T1	7	6
	T2	2	2
	T3	1	2
	T4	2	2
	T5	1	2
	T6	1	1
	T7	2	1
	T8	4	4
	T9	8	7
	T10	3	3
	T11	8	6
	T12	9	8
	T13	15	14

The effect of fabric relaxation on pressure levels was also assessed by measuring the pressures applied to a mannequin immediately after and 24 hours after placing the SCGs on the mannequin. The expected effect of fabric relaxation on pressure levels was mainly noticeable at the leg hem (B1) and biceps (T11) as shown in Table 7.7. However, at some locations pressure levels were slightly higher after 24 hours. Hence, there was no clear relationship between fabric relaxation and applied pressure levels.

Table 7.7: Effects of fabric relaxation on pressure levels

Pressure Measurements (mmHg) on AlvaForm Soft Series Mannequin (size 12)					
Tights (size M)			Top (size M)		
Point of Measure	After WTs	After WTs, worn 24h	Point of Measure	After WTs	After WTs, worn 24h
B1	18	14	T1	4	7
B2	13	11	T2	2	1.5
B3	8	8	T3	1	1
B4	9	8	T4	2	2
B5	9	8	T5	2	2
B6	7.5	9	T6	1	1
B7	4.5	4	T7	1	1
B8	3	3	T8	3	4
B9	10	10	T9	6	7
			T10	2.5	2
			T11	6.5	3
			T12	4.5	6
			T13	12.5	11

Pressure levels under seams were also examined on a mannequin as presented in Table 7.8. There were no large variations between pressure levels under seams and pressures next to the seams. The small variations of 1mmHg and 2mmHg could be associated with variations in body curvature at the different locations. These results are in opposition to findings from Allsop (2012) who reported pressure drops under seams. However, the researcher utilised a different PM device (Tekscan), which is based on semi-conductive material measuring changes in electrical resistance (Tekscan Inc., 2014), visualising pressure levels over a bigger surface, whilst the pneumatic PicoPress® PM device used in this study measured the applied pressure at a distinct location. The different results could, thus, be based on the different measurement methods. It could, however, also be related to the 'A-seams' used in the Skins SCGs. The compression top assessed in Allsop's (2012) study featured ISO 607 wide cover seams. Perhaps 'A-seams' offer less variation in pressure application than conventional flat cover stitches. Further research is required to confirm this.

Table 7.8: Pressure measurements in relation to garment seams measured on mannequin

SCGs	PM location		Pressure (mmHg)
Top M – after WTs, after 5 washes	S-US	Under shoulder seam	4
	S-NS	Next to shoulder seam	4
Tights S – after WTs, after 5 washes	C-US	Under lower calf seam	10
	C-NS	Next to lower calf seam	12
	K-US	Under seam at topend of knee panel	10
	K-NS	Next to seam at topend of knee panel	9

Pressure Measurements in Different Test Conditions

Pressures were measured under the different testing conditions outlined in section 4.4.3.2. The aim was to explore how differences in garment sizes and moisture content affect pressure levels. The pressure values measured in the different test conditions are presented in Table 7.9.

Table 7.9: Pressure measurements in different test conditions on mannequin

Point of Measure		US-C	AS-C	OS-C	W-C
		Size S	Size M	Size L	Tights: S Top: M
Tights	B1	16	18	26	17
	B2	12	16	15	14
	B3	11	9	13	12
	B4	12	10	9	11
	B5	11	10	9	12
	B6	13	9	9	6
	B7	7	7	4	5
	B8	4	3	3	3
	B9	14	13	8	17
Top	T1	6	7	10	7
	T2	3	2	1	2
	T3	2	1	1	1
	T4	4	2	2	3
	T5	2	1	2	2
	T6	2	1	2	1
	T7	3	2	2	1
	T8	5	4	3	3
	T9	8	8	8	6
	T10	3	3	3	1
	T11	11	8	4	6

Point of Measure	US-C	AS-C	OS-C	W-C
	Size S	Size M	Size L	Tights: S Top: M
T12	13	9	5	13
T13	22	15	15	20

US-C = undersized condition; AS-C = adequately sized condition; OS-C = oversized condition; W-C = Wet condition

The lowest pressure values for all measuring conditions were recorded 10cm below the navel (B8) for the compression tights (3-4mmHg) and at the front oblique (T3) and the front chest muscle (T6) for the compression top (1-2mmHg). The highest pressure levels were recorded at the hem (B1 - inner ankle) of the compression tights (16-26mmHg) and at the sleeve hem (T13 - inner wrist) of the compression top (14-22mmHg). The overall maximum value of 26mmHg was measured in size Large at B1. It was surprising that an oversized garment elicited the highest amount of pressure, however, this could be related to the fact that the garment was unworn when the measurement was taken, whilst the other garments had previously been dressed on a mannequin. The hems of the SCGs were bonded with adhesive film. The adhesive film made the hems stiffer than the rest of the garments, which could have contributed to the higher pressure levels at the hems, but it also inhibited the hems from recovering to their original size. The leg and sleeve opening widths both increased by 0.9cm and 0.6cm, respectively, from before the WTs to after WTs. Whilst they decreased slightly after washing, a residual difference of 0.5cm and 0.4cm remained.

The highest variation of pressure levels was detected at measurement point B1 (hem at inside leg), B9 (waistband at centre front) and B6 (gluteus maximus) with differences in pressure values between the measurement conditions of up to 10mmHg, 9mmHg and 7mmHg, respectively. The pressure values for the different locations recorded at the torso did not vary as widely as the pressure values of the tights. The highest variation of pressure levels across the different conditions was observed at the sleeves with differences of up to 7mmHg at T11 (inner biceps) and 8mmHg at T12 (inner forearm) and T13 (sleeve hem). Pressure levels at the torso were generally lower than pressures at the sleeves. When applying gradual compression, SCG brands generally intend to have the highest level of pressure at the distal end of the limbs to promote venous return. It is, thus, not surprising that the lowest pressure values were recorded at the torso, i.e. close to the heart. Pressure levels at the top of the shoulder (T9) were higher than pressures at the rest of the torso. This finding goes in line with previous research (Allsop, 2012), which reported high pressure levels of men's compression tops at the top of the shoulder with a dramatic drop in pressure at the chest, which was also observed in this study.

There were no substantial differences between the average pressures measured across the lower body and the upper body for each measurement condition with pressures ranging from 9.8mmHg (wet condition) to 11.1mmHg (size S) for the compression tights and 4.5mmHg (size L; wet condition) to 6.5mmHg (size S) for the compression top. Mean pressures were, thus, highest in size S. Based on Friedman tests, there were no statistically significant differences between pressures measured for different garment sizes. However, there was a statistically significant difference in measured pressures depending on what size compression top the mannequin wore, χ^2 (df = 2) = 10.12, p = 0.006. Post hoc analyses with Wilcoxon signed-rank tests were conducted with Bonferroni correction, resulting in a significance level set at $p < 0.017$. Median (IQR) pressure for sizes Small, Medium and Large was 4mmHg (2.5 to 9.5), 3mmHg (1.5 to 8) and 3mmHg (2 to 6.5), respectively. There were no significant differences in pressures between sizes Small and Large (Z = -1.965, p = 0.049) or Medium and Large (Z = -0.690, p = 0.490), despite an overall reduction in pressure in size Large. However, there was a statistically significant decrease in pressure levels in the Medium-sized top compared to the Small-sized top (Z = -2.653, p = 0.008), which was especially prevalent at the sleeves.

Wilcoxon signed rank tests revealed no statistically significant differences between the pressure values measured in dry and wet conditions.

Pressures of the compression tights were distributed in a decreasing gradient from the ankle to the calf (B1 to B3), but not for the knee (B4) and mid-thigh (B5). Pressures around the hip area (B7, B8) were slightly lower with a sharp increase in pressure at the waistband, which could be accredited to the strong elastic at the front of the waistband. The pressure distribution of the compression top was relatively even around the mid-section, where pressures were low, with a higher value at the hem due to the elastic webbing at the hem. Pressure distribution at the sleeves was gradual with pressures decreasing from the wrist to the biceps (T13 to T11).

Comparison of Pressure Data to Different SCGs

As there is no ‘optimal’ pressure level for SCGs and Skins did not state their intended pressure range, pressures applied by SCGs from a different brand were also measured to have a point of comparison. The Sub Sports Elite RX Active Women’s Long Sleeve Top and Elite RX Active Women’s Leggings in size Medium were made from 80% nylon and 20% elastane according to the care label. Further details about the garments can be found in Appendix O. The pressure values measured on a mannequin are shown in Table 7.10.

Table 7.10: Pressure measurements of Sub Sports SCGs on mannequin A

SUB RX Active Women's SCGs - size M			
Tights		Top	
Point of Measure	Pressure (mmHg)	Point of Measure	Pressure (mmHg)
B1	11	T1	9
B2	9.5	T2	2
B3	14	T3	0.5
B4	15.5	T4	2
B5	10	T5	2.5
B6	12.5	T6	2.5
B7	6	T7	2
B8	5	T8	5
B9	7	T9	6
		T10	1
		T11	6
		T12	10
		T13	14.5

Overall, the measured pressure levels of the compression top did not vary substantially between the Skins and Sub Sports compression tops with a maximum difference of 2mmHg and an overall mean pressure of 4.9mmHg for both compression tops. The pressure distribution of the Sub Sports top was comparable to the Skins top, but the pressure gradient from wrist to biceps at the sleeve was slightly more pronounced in the Sub Sports compression top. Bigger variations in pressure levels were evident in the compression tights of the two brands. The biggest variations in pressure (>5mmHg) were at the ankle and lower calf, where pressure levels were lower in the Sub Sports garments, and at the calf and knee, where pressure levels were higher in the Sub Sports garments. Pressure at the waistband was also lower. The pressure distribution of the Sub Sports tights was not gradual as the pressure was lower at the ankle and lower calf than at the calf and knee. Overall, pressure levels of the Skins compression tights were slightly higher with a mean pressure of 10.6mmHg compared to 10.1mmHg for the Sub Sports garment.

7.3.2.4 Effects of Use and Care on Compression

The Skins A400 SCGs were visually assessed after the WTs (described in the subsequent chapter) had been conducted. There were signs of wear at the 'A-seams' of the compression tights (see Figure 7.12-a). The seams were still intact, however, it appeared that some fibres had become loose. It is believed that this was due to the use of tape as markers during the WTs. This could potentially weaken the seam. Some tears were also visible on the reflective glass bead print on the compression top (see Figure 7.12-b).

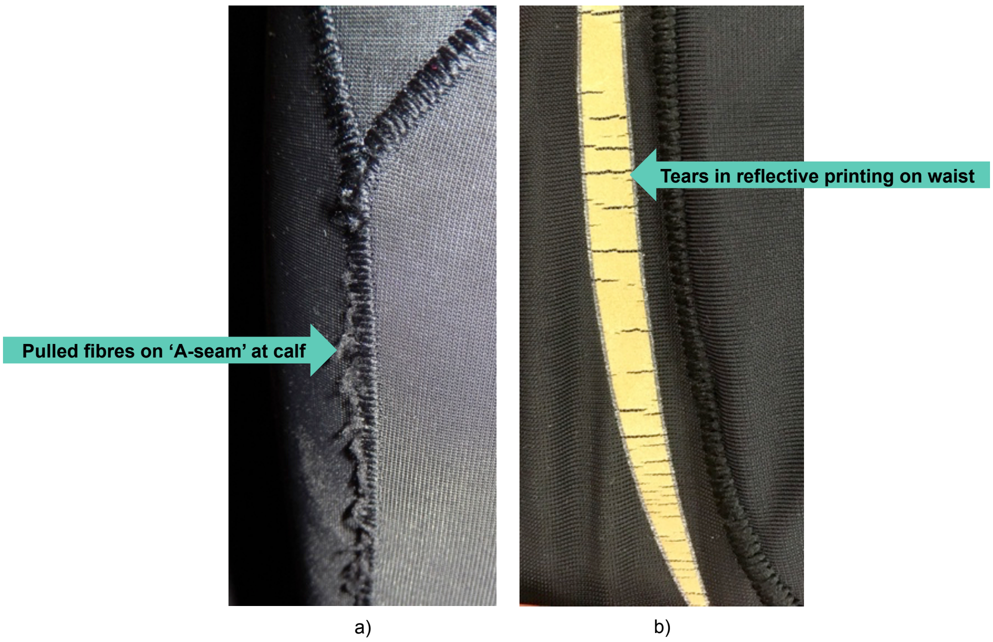


Figure 7.12: Signs of wear: a) Loose fibres at the calf seam of the compression tights after the WTs; b) Tears in the reflective printing on the torso of the compression top after the WTs

The compression top in size Medium and the compression tights in size Small were measured before and after the WTs as well as after one wash and after five wash and dry cycles. The results are shown in Table 7.11 and Table 7.12 for the compression top and tights, respectively.

Table 7.11: Garment flat measurements of compression top before WTs, after WTs, after one wash and after five washes

Garment Flat Measurements (cm) - Top size M - Repeated Measures					
	Point of Measure	**Pre-WTs**	**Post-WTs**	**Post-1W**	**Post-5W**
1	Front length (side neck point to hem)	56.3	55.8	55.6	55.5
2	Centre back length	54.2	54.2	54.0	53.5
3	Side length	39.2	37.3	37.8	37.3
4	Chest width (2.5cm down from underarm)	34.5	35.9	35.5	35.5
5	Across chest (6.5cm down from centre neck seam)	31.3	32	31.7	31.4
6	Across back (10cm down from centre neck seam)	28.5	29.7	29.6	29.4
7	Waist width (40cm down from shoulder high point)	30.4	31.7	31.1	30.9
8	Bottom opening width (edge to edge, straight)	34.5	34.75	34.2	33.9
9	Sleeve length top armhole (shoulder high point to sleeve opening)	59.8	60.4	60.1	59.7
10	Sleeve length underarm	46.2	46.4	46.7	46.3
11	Curved armhole width	18.7	19.7	19.4	19.3
12	Sleeve width (2.5cm below armhole, parallel to sleeve opening)	14	13.8	14.0	14.4
13	Elbow width (1/2 of underarm sleeve length)	10.1	10	10	10
14	Sleeve opening width	7	7.6	7.3	7.4
15	Neck depth front	8.0	8.45	8.0	8.0
16	Neck drop front	9.1	9.4	9.1	9.0
17	Neck drop back	1.0	0.9	1.1	1.0
18	Neck width	18.2	19	19.4	18.9
19	Neck base	24.3	29.6	28.8	28.9

Pre-WTs = before WTs; Post-WTs = after WTs; Post-1W = after 1 wash cycle; Post-5W = after 5 wash cycles

Table 7.12: Garment flat measurements of compression tights before WTs, after WTs, after one wash and after five washes

Garment Flat Measurements (cm) - Tights - size S - Repeated Measures					
	Point of Measure	**Pre-WTs**	**Post-WTs**	**Post-1W**	**Post-5W**
1	Waistband depth CF	3.5	3.6	3.6	3.6
2	Waistband depth CB	6.6	6.8	6.9	6.9
3	Waistband depth side	6.6	6.7	6.5	6.7

Garment Flat Measurements (cm) - Tights - size S - Repeated Measures					
	Point of Measure	Pre-WTs	Post-WTs	Post-1W	Post-5W
4	Waistband width front (measured straight at top edge)	32.2	32.6	32.6	32.5
5	Hip width (10cm down from top edge)	31.8	32.2	32.0	32.0
6	Inseam (measured along seam, CF seam to hem)	69.6	68.7	68.3	68.5
7	Outseam/length (top edge to hem)	85.1	84.1	83.9	84.4
8	Front rise (top edge to crotch seam intersection, measured along curve)	18.3	19.8	19.9	19.2
9	Back rise (top edge to front seam, measured along curve)	27.6	28.2	27.4	27.2
10	Thigh width (5cm down from crotch)	17.2	17.2	17.7	17.7
11	Knee width (½ of inseam length)	11.7	12.1	11.9	11.7
12	Calf width (25cm up from bottom hem)	10.7	11.3	11.3	11.2
13	Leg opening width (measured straight)	8.6	9.5	9.2	9.1

Pre-WTs = before WTs; Post-WTs = after WTs; Post-1W = after 1 wash cycle; Post-5W = after 5 wash cycles

Friedman tests revealed that there were statistically significant differences between garment flat measurements of the SCGs recorded at the four different points in time for the compression tights in size S (χ^2 (df = 3) = 8.49, p = 0.037), however, post-hoc Wilcoxon tests with Bonferroni correction (p < 0.0083) determined that there was no significant difference between garment measurements at the individual measurement occasions.

PMs were also recorded at the four different points in time on the compression top in size Medium and the compression tights in size Small on a mannequin as presented in Table 7.13. No statistically significant differences between the pressure values could be identified using Friedman tests and Wilcoxon post-hoc tests with Bonferroni correction.

Table 7.13: Pressure measurements of SCGs before WTs, after WTs, after one wash and after five washes

Pressure Measurements on Mannequin (mmHg) - Repeated Measures					
	Point of Measure	Pre-WTs	Post-WTs	Post-1W	Post-5W
Tights - size S	B1	16	16	14	15
	B2	12	15	14	11
	B3	11	11	13	11
	B4	12	11.5	13.5	11
	B5	11	12	13	8
	B6	13	11	10	10

Pressure Measurements on Mannequin (mmHg) - Repeated Measures					
	Point of Measure	Pre-WTs	Post-WTs	Post-1W	Post-5W
	B7	7	5	5	5
	B8	4	4	4	4
	B9	14	13	19	12.5
Top - size M	T1	7	6	7	5.5
	T2	2.15	1	2	2
	T3	1.15	1	1	1
	T4	2.5	2	2	2
	T5	1.5	1.5	2	2
	T6	1	1.5	1.5	1
	T7	1.5	1.5	1.5	1
	T8	3.5	5	3.5	4
	T9	7	10	7	6
	T10	2	2	4	3.5
	T11	7.15	5	5.5	7.5
	T12	11.15	4	7	6
	T13	17.5	12	13	11.5

Pre-WTs = before WTs; Post-WTs = after WTs; Post-1W = after 1 wash cycle; Post-5W = after 5 wash cycles

Based on the results of the stretch and recovery tests in Study 1, it was to be expected that the SCGs were slightly larger after the WTs, as Fabric A does not fully recover after being stretched, especially for the garments that had been worn the most frequently during the WTs (size S tights and size M top). However, there were no significant differences between garment flat measurements of the compression top. This could be related to the fact that the top was not stretched as much as the tights, as pressures measured on the top were lower. The only significant differences identified were in size Small of the compression tights between the ‘after WTs’ and ‘after 5 washes’ conditions. It could have been expected that there would also be a significant difference between the garment flat measurements of the ‘before WTs’ and ‘after WTs’ conditions. It is interesting to note, though, that the variations in garment measurements of the compression tights in size S did not translate into variations in pressure values.

7.4 Size Chart Review

The third and final part of Study 3 was the review of size charts for commercial compression sportswear.

7.4.1 Objectives of Size Chart Review

The objectives of the size chart review were:

4. To identify sizing methodologies used by SCG brands.
5. To compare sizing systems used by different brands.
6. To assess the suitability of different sizing systems for the WT participants.

7.4.2 Skins A400 Size Charts

According to Skins (2016), the size chart for the A400 women's compression tights is based on 400 key fitting points that were established from 3D body scans of hundreds of recreational and professional athletes and the analysis of over 800,000 measurements from each athlete. The brand claims that the research led to a better fit for different body shapes for women and that "[n]o product in the world pays such attention to your body size and shape. Which is why nothing fits – or works – quite like SKINS 400 Series" (Skins, 2016).

The size chart for the Skins A400 compression top is based on the wearer's chest circumference. This is the standard primary dimension used for the determination of size designations for knitted tops or undervests for women (British Standards Institution, 2017c). Secondary dimensions are frequently used to determine size categories. Height is defined by the relevant British Standard (BS ISO 8559-2-2017) as a secondary dimension for knitted tops and height and hip girth for undervests. However, no secondary dimensions are used for the Skins A400 upper body size chart. The size chart encompasses chest girths of 69 to 112cm and is divided into five size categories from XS to XL. The range of chest circumferences defining sizes XS and XL is larger than the circumference range for sizes S, M and L as is visible from the grid in Figure 7.13.

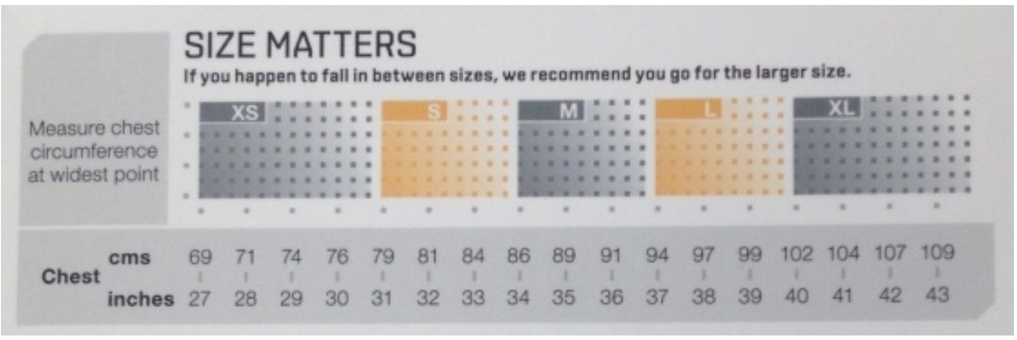


Figure 7.13: Size chart for Skins A400 compression top (from Skins packaging)

The size chart for the Skins A400 compression tights is not based on circumference measurements, but on weight and height of the intended wearer. The size chart is displayed as a grid with height and weight as coordinates. The intended wearer's weight (primary dimension) is plotted against their height (secondary dimension) to obtain the appropriate size designation. This type of sizing system, hereafter referred to as BMI (body mass index) system, is generally used for hosiery. Whilst sizing systems for leggings tend to use hip girth as primary dimension with height and inside leg length as potential secondary dimensions (British Standards Institution, 2017c), hosiery sizing systems are based on height or hip girth as primary dimension with hip girth or height as secondary dimension (British Standards Institution, 2017a). Weight is believed to be closely correlated to hip girth, thus, hip girth is frequently replaced by weight in these sizing systems to facilitate size selection for consumers who tend to be more familiar with their weight than hip circumference measurement (British Standards Institution, 2017a). The size chart of the compression tights consists of the same five size designations as the compression top: XS, S, M, L and XL. The sizing categories are distributed diagonally across the weight/height grid as is evident from Figure 7.14.

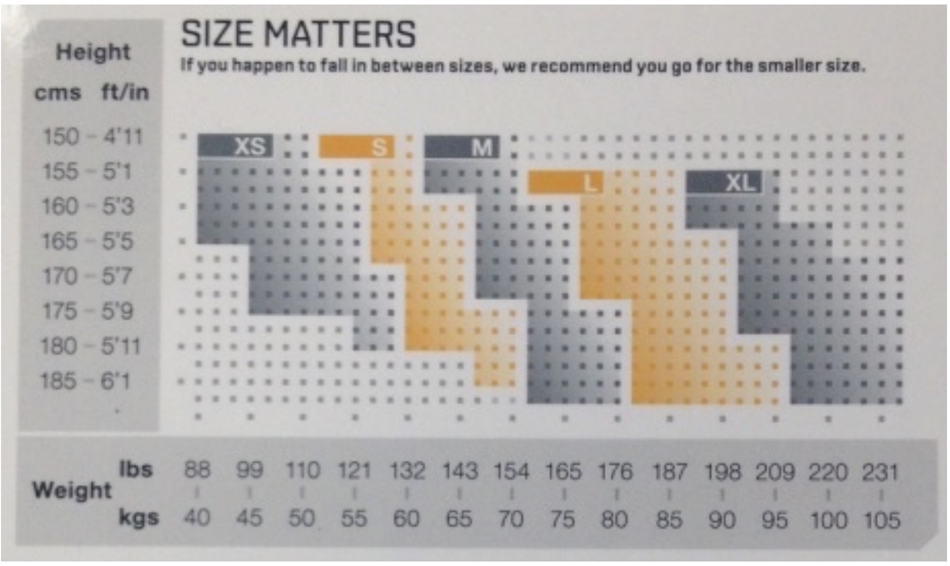


Figure 7.14: Size chart for Skins A400 compression tights (from Skins packaging)

7.4.3 Comparison of Sizing Systems for Conventional and Compression Sportswear

Size charts for women’s tops and bottoms of eight generic sportswear brands and eleven specialist compression sportswear brands were collected from the brands’ websites and reviewed. All eight generic sportswear brands offered compression garments among their wide sportswear ranges, but did not have specific size charts for SCGs. The aim was to identify potential differences in sizing between conventional and compression sportswear.

The eight conventional sportswear size charts for bottoms were generally based on waist and hip circumference measurements with many brands also including inseam length (n = 5) or height (n = 1), whilst sizing for tops was usually based on chest, waist and hip circumferences, as shown in Table 7.14.

Table 7.14: Body measurements used for conventional women’s sportswear size charts

					Torso girth				Limb girth
	Brand	**Weight**	**Height**	**Inseam length**	**Chest**	**Under bust**	**Waist**	**Hip**	**Thigh**
Lower body garments	Adidas			x			x	x	
	Nike			x			x	x	
	Reebok			x			x	x	
	Under Armour						x	x	
	Lululemon			x			x	x	
	Sweaty Betty			x			x	x	
	Canterbury						x	x	
	Asics		x				x	x	
Upper body garments	Adidas				x		x	x	
	Nike				x		x	x	
	Reebok				x		x	x	
	Under Armour				x		x	x	
	Lululemon				x				
	Sweaty Betty				x		x	x	
	Canterbury				x		x	x	
	Asics		x		x		x	x	

The body measurements used for the sizing of compression tops and bottoms by the eleven SCG specialists included in the size chart review are summarised in Table 7.15. It is apparent that there were more variations in the sizing approaches applied by the different brands compared to conventional sportswear. The sizing approach for compression tights were therefore divided into four categories: 1) BMI systems, 2) torso girth systems, 3) limb girth systems and 4) a combination of

BMI and torso girth systems. Three of the compression sportswear brands based their size charts on BMI systems like Skins. These systems vary most notably from conventional sizing systems, as no circumference measurements are considered. However, four of the size charts under investigation were based on the conventional system of torso circumferences. It is interesting to note that companies, like Compressport and CEP with roots in medical compression, use limb circumference measurements for size determination. Using limb girth measurements is the common system applied in fitting medical compression stockings (MCS). Two brands also used a combination of BMI/height and torso girth systems.

Table 7.15: Body measurements used for women's compression sportswear size charts

	Brand	**Weight**	**Height**	**Inseam length**	**Torso girth**				**Limb girth**
					Chest	**Under bust**	**Waist**	**Hip**	**Thigh**
Lower body garments	***Skins***	x	x						
	2XU	x	x						
	Body Science	x	x						
	CW-X	x	x						
	Sub Sports						x		
	Enerskin							x	
	Virus						x	x	
	Intelliskin						x	x	
	Compressport								x
	CEP								x
	Linebreak	x	x		x		x	x	
	X-Bionic		x				x	x	
Upper body garments	***Skins***				x				
	2XU				x				
	Body Science	x	x						
	CW-X				x				
	Sub Sports				x		x		
	Enerskin					x			
	Virus				x				
	Intelliskin	x			x	x	x	x	
	Compressport				x				
	CEP				x				
	Linebreak	x	x		x		x	x	
	X-Bionic		x		x				

The size charts for compression tops were mainly based on torso girths (n = 7), like conventional sportswear. Four brands only using chest circumference measurements for determination of sizing similar to the Skins size chart. Body Science use the same BMI system for tops and bottoms, whilst three brands use a combination of torso girth and height and/or weight measurements.

The fit of SCGs is critical to ensure the desired level of pressure is applied to the underlying body. Because of the second-skin nature of SCGs and their high elasticity, some SCG brands have applied the same sizing approach used for hosiery. Whether this approach is better than conventional sizing systems based on circumference measurements is questionable. However, it can be assumed that a different sizing approach than conventional torso girth sportswear sizing systems is required for SCGs, as pressure application is most critical at the limbs. There is a case for using limb circumferences as the defining size categories for compression tights since Laplace's Law defines pressure as the ratio of fabric tension and the radius of the underlying object. However, fit around the torso is important too for optimal comfort and support. Perhaps a combination of limb circumferences and other measurements would be the best solution for compression tights. However, there is currently no research on sizing systems for SCGs. The WTs in Study 3 were hoped to give further insight into how the Skins A400 BMI sizing system performs for the WT participants.

7.4.4 Comparison of Sizing Systems for Sports Compression Garments

With the aim to compare different sizing systems applied by SCG specialists, the Skins size chart for women's A400 compression tights was mapped against the other BMI-based size charts under investigation in Figure 7.15 to Figure 7.18. It is obvious that the 2XU size chart (Figure 7.15) encompasses the widest range of body dimensions, as the brand offers more size categories (XXS to XXL) and tall options for the core sizes Small, Medium and Large. The Linebreak size chart is the only size chart based on a linear system, which assumes that an increase in weight linearly correlates with an increase in height. Figure 7.16 illustrates that the sizing system includes a very narrow range of body measurements, despite offering the same number of sizes as Skins. CW-X (Figure 7.17) also incorporates a smaller range of body dimensions than Skins despite the same number of sizes. The CW-X size grid is the flattest of all BMI grids covering the smallest range of height measurements. The Body Science (Figure 7.18) size chart encompasses smaller body dimensions than the Skins size chart, but does not include as many large body dimensions. It is the only size grid based on rectangles as size categories rather than gradual stepwise shapes.

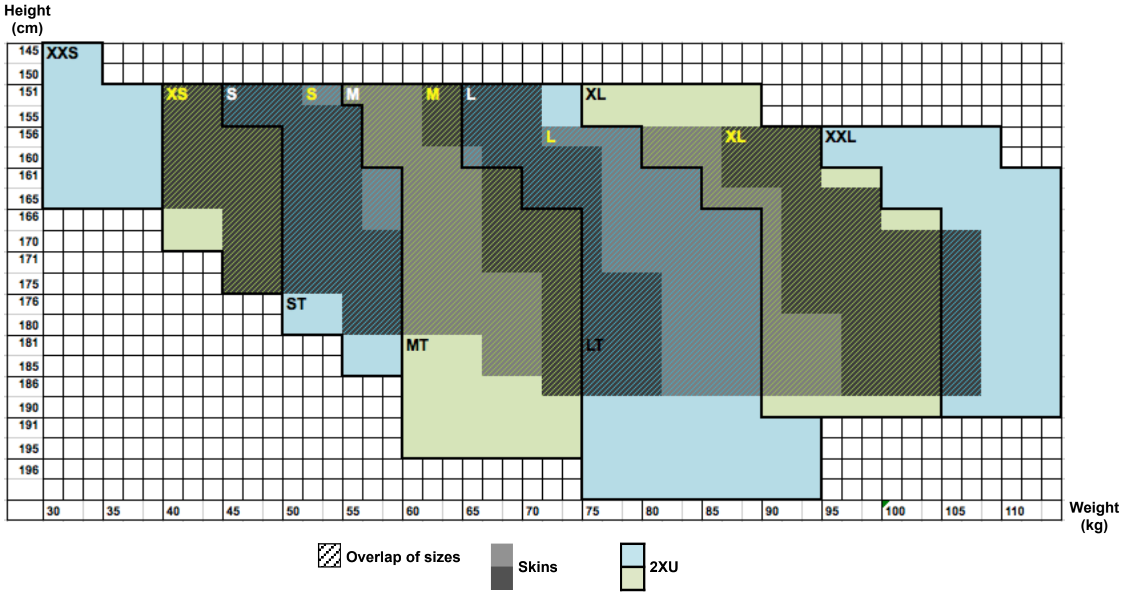


Figure 7.15: Comparison of lower body Skins A400 women's size chart and 2XU women's size chart

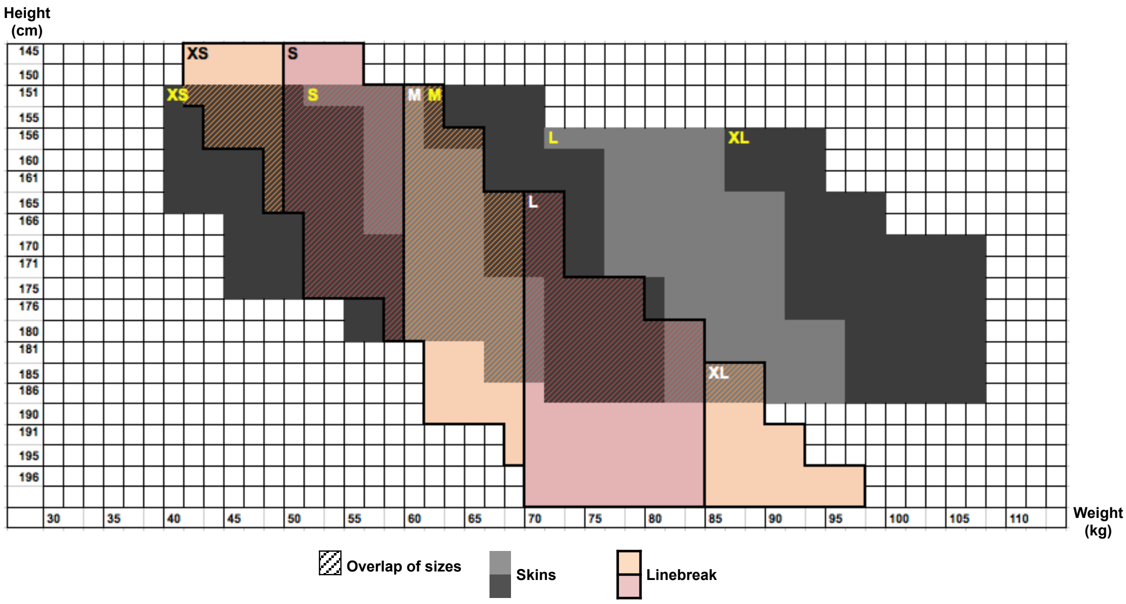


Figure 7.16: Comparison of lower body Skins A400 women's size chart and Linebreak women's size chart

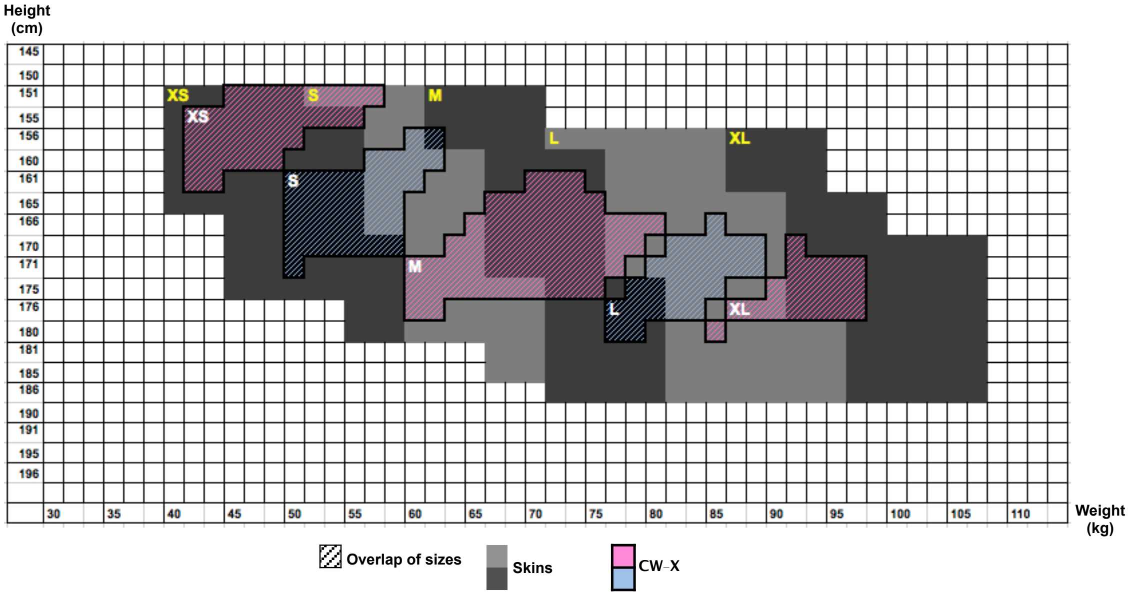


Figure 7.17: Comparison of lower body Skins A400 women's size chart and CW-X women's size chart

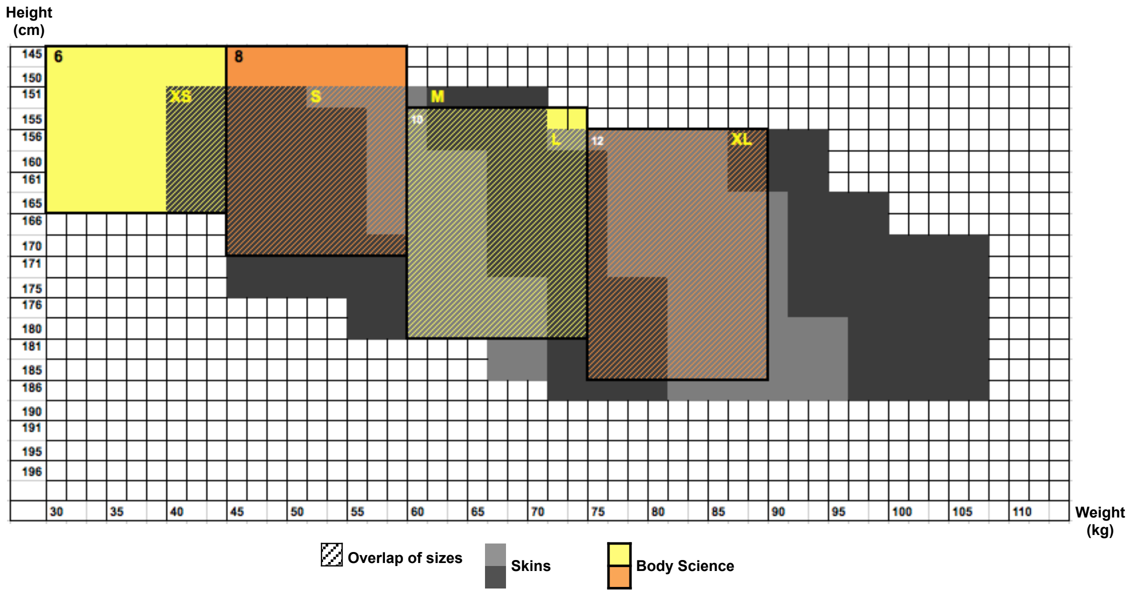


Figure 7.18: Comparison of lower body Skins A400 women's size chart and Body Science women's size chart

Variations in size distribution on the height/weight grid could be related to variations in deformation and extensibility behaviour of the fabric (British Standards Institution, 2017a). Regardless of fabric properties, sizing across different brands generally differs because brands base their size charts on the specific body dimensions of their target consumers (refer 3.3.6).

Compressport and CEP are the only two brands using thigh girths as primary dimensions for compression tights. A comparison of the two size charts is presented in Table 7.16. CEP's sizes range from XS to XXL with Compressport only offering four sizes. Consequently, CEP compression tights fit a wider range of thigh girths from 40 to 75cm. Both brands use standard grades of 5cm, however, the girth ranges within each size designation of CEP overlap as each size category covers a range of 10cm.

Table 7.16: Comparison of limb girth sizing systems for sports compression tights

Brand	Thigh circumference (cm)					
	XS	S	M	L	XL	XXL
Compressport	44-49	49-54	54-59	59-64	-	-
CEP	40-50	45-55	50-60	55-65	60-70	60-75

Table 7.17 shows the torso girths that are used by the SCG brands under investigation for size determination of compression tights. As is common in sizing across different brands, the hip and waist circumferences used to define the different size categories vary between brands. It is obvious that the hip girths defining the Virus sizing system are considerably smaller than the hip girth values of the other brands. As a consequence, it only encompasses hip girths of up to 108cm. Enerskin offers the biggest size range with eleven sizes, covering hip girths from 80 to 134.5cm. The fit range and grade increments applied by the different brands are listed in Table 7.18. Three out of five of the SCG brands applied variable grades for the hip girth between the different size categories, whilst three out of five used equal grades for the waist circumference.

Table 7.17: Comparison of size range for torso girth sizing systems for sports compression tights

		Waist and hip circumference (cm)										
		XS	**XS+**	**S**	**S+**	**M**	**M+**	**L**	**L+**	**XL**	**XXL**	**XXXL**
Sub Sports	Waist	61-66	-	66-71	-	71-76	-	76-81	-	81-86	86-91	-
	Hip	-	-	-	-	-	-	-	-	-	-	-
Enerskin	Waist	-	-	-	-	-	-	-	-	-	-	-
	Hip	80-84.5	85-89.5	90-94.5	95-99.5	100-104.5	105-109.5	110-114.5	115-119.5	120-124.5	125-129.5	130-134.5
Virus	Waist	64	-	69	-	74	-	79	-	84	-	-
	Hip	79-83	-	84-88	-	89-93	-	94-100	-	101-108	-	-
Intelliskin	Waist	61-66	-	66-71	-	71-81	-	81-86	-	86-97	-	-
	Hip	86-91	-	91-97	-	97-102	-	102-112	-	112-117	-	-
Linebreak[a]	Waist	66	-	71	-	76	-	81	-	86	-	-
	Hip	92	-	97	-	102	-	107	-	112	-	-
X-Bionic[b]	Waist	60-65	-	66-73	-	74-81	-	82-89	-	91-102	-	-
	Hip	88-91	-	92-98	-	99-104	-	105-112	-	113-121	-	-

a: Also considering height and weight in determining size
b: Also considering height in determining size

Table 7.18: Fit range and grades of reviewed torso girth systems for sports compression tights

	Fit range: hip girth	Girth range within each size designation	Grade increments[a]	Fit range: waist girth	Girth range within each size designation	Grade increments[a]
Sub Sports	-	-	-	61-91	5	5
Enerskin	80-134.5	4.5	5	-	-	-
Virus	79-180	4, 4, 4, 6, 7	5, 5, 5, 7	64-84	0	5
Intelliskin	86-117	5, 6, 5, 10, 5	5, 6, 5, 10	61-97	5, 5, 10, 5, 11	5, 5, 10, 5
Linebreak	92-112	0	5	66-86	0	5
X-Bionic	88-121	3, 6, 5, 7, 8	4, 7, 6, 8	60-102	5, 7, 7, 7, 11	6, 8, 8, 9

a: Lowest value of x – lowest value of (x-1) (x= size specification)
All measurements in cm

The chest girth values used by the SCG brands for size determination of compression tops are presented in Table 7.19 with the fit range and grade increments applied by the different companies listed in Table 7.20. The different SCG brands offer varying numbers of size categories. Most brands offer five different size categories (XS to XL), however, two brands only offer four sizes (XS to L), whilst another two brands offer six size categories (XS to XXL). Again, the chest circumference values within each size category vary between brands. The chest girths defined by Compressport for sizes XS and S are larger than all other brands. However, this is not the case for sizes M and L, as the grade increment applied by Compresssport is lower than the grades used by other brands. The brand is one of three brands using equal grades between the different size categories. Compressport offers the narrowest range of chest circumferences from 84 to 100cm, whilst Intelliskin incorporates the widest range from 71 to 117cm.

Table 7.19: Comparison of different size ranges for commercial compression tops

Brand	Chest girth (cm)					
	XS	S	M	L	XL	XXL
Skins	69-78	79-85	86-93	94-101	102-110	-
2XU	74-81	81-89	89-96	96-102	102-107	-
CW-X	76-83	83-89	89-95	95-102	-	-
Sub Sports[a]	74-81	81-89	89-96	96-104	104-112	112-119
Virus	79	84	89	94	99	-
Intelliskin[b]	71-81	76-86	86-97	91-102	91-112	102-117
Compressport	84-88	88-92	92-96	96-100	-	-
CEP	78-82	82-87	87-93	93-99	99-105	-
Linebreak[c]	83	88	93	98	103	-
X-Bionic[d]	78-81	82-89	90-97	98-107	108-119	-

a: Also using waist girth to determine size
b: Also using waist girth, hip girth, under bust girth and weight to determine size
c: Also using waist girth, hip girth, height and weight to determine size
d: Also using height to determine size

Table 7.20: Fit range and grades of commercial compression tops

Brand	Fit range: chest girth	Girth range within each size designation	Grade increments[a]
Skins	69-110	9, 6, 7, 7, 8	10, 7, 8, 8
2XU	74-107	7, 8, 7, 6, 5	7, 8, 7, 6, 5
CW-X	76-102	7, 6, 6, 7	7, 6, 6, 7
Sub Sports	74-119	7, 8, 7, 8, 8, 7	7, 8, 7, 8, 8
Virus	79-99	0	5
Intelliskin	71-117	10, 10, 11, 11, 21, 15	5, 10, 5, 0, 11

Brand	Fit range: chest girth	Girth range within each size designation	Grade increments[a]
Compressport	84-100	4	4
CEP	78-105	4, 5, 6, 6, 6	4, 5, 6, 6, 6
Linebreak	83-103	0	5
X-Bionic	78-119	3, 7, 7, 9, 11	4, 8, 8, 10

a: Lowest value of x – lowest value of (x-1) (x= size specification)
All measurements in cm

7.4.5 Post-Wearer Trial Size Chart Assessment

To examine whether sizing systems combining girth measurements with height and/or weight measurements are a feasible sizing approach, the WT participants' body measurements, obtained from body scans during the WTs, were mapped against the size charts. At first, the Linebreak size chart (Figure 7.19) was assessed. The primary dimensions of the size chart were weight and height, but in addition measurement ranges for chest, waist and hip girth of the intended wearer were provided. It was the only size chart that combined weight and circumference measurements to determine size categories for compression tights. Chest, waist and hip circumferences in the size chart increased with weight, however no height variations were accounted for in the sizing system as height increased linearly with increasing weight. Taking into account all body dimensions provided by the size chart, only two (both size L) out of 33 WT participants would have fitted into Linebreak SCGs. Six participants did not fit into the height/weight grid, whilst the other 25 participants did not match the body circumferences with variations of a minimum of 10cm mainly at the waist.

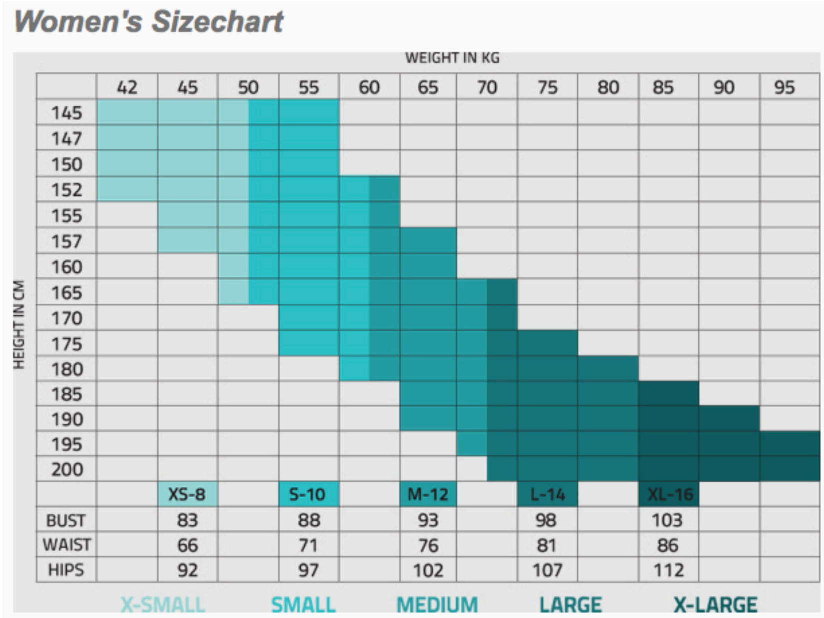
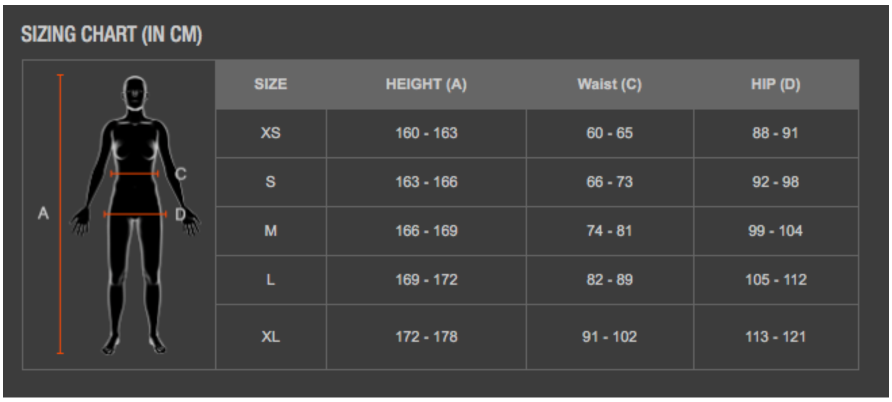


Figure 7.19: Linebreak size chart for women's compression sportswear (Linebreak, 2016)

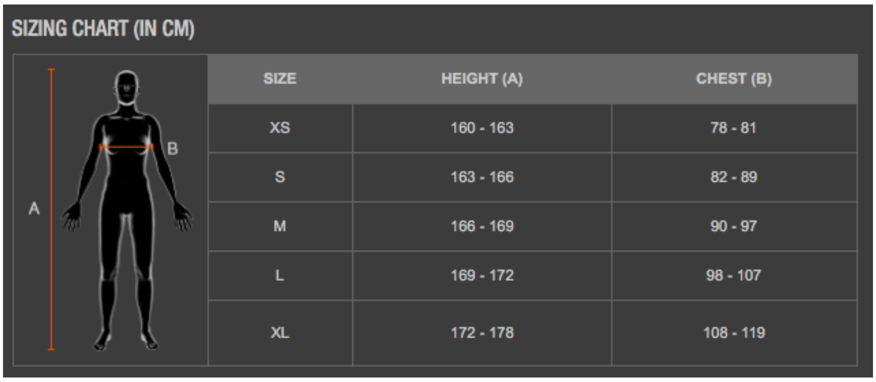
Next, the X-Bionic size chart for women's compression tights (Figure 7.20) was assessed. The brand's size chart for compression tights was based on height as well as waist and hip circumferences. The sizing system had similarities to conventional sportswear sizing, but used height instead of inseam measurements. The underlying assumption of the system was that height increases linearly with increasing waist and hip circumferences. Again, only two (size L and XL) out of the 33 WT participants would have fitted into X-Bionic tights using this size chart.


SIZING CHART (IN CM)

SIZE	HEIGHT (A)	Waist (C)	HIP (D)
XS	160 - 163	60 - 65	88 - 91
S	163 - 166	66 - 73	92 - 98
M	166 - 169	74 - 81	99 - 104
L	169 - 172	82 - 89	105 - 112
XL	172 - 178	91 - 102	113 - 121

Figure 7.20: X-Bionic size chart for women's compression tights (X-Bionic, 2016)

The X-Bionic size chart for women's compression tops (Figure 7.21) was based on height and chest circumferences. As the size chart for compression tights, it underlay the assumption that there is a positive linear correlation between height and chest circumference. Based on this size chart, four (size S, 2x M and L) out of 33 WT participants would have fitted into X-Bionic compression tops. The findings show that the majority of WT participants would not fit into SCGs from Linebreak or X-Bionic designed to the discussed size charts calling into question the applied sizing methodologies. It has been reported that size charts based on linear sizing are generally not based on actual body measurement dispersion of the target population (Gill, 2015). It is assumed that this is the case here, hence the poor rate of fit for the WT participants.


SIZING CHART (IN CM)

SIZE	HEIGHT (A)	CHEST (B)
XS	160 - 163	78 - 81
S	163 - 166	82 - 89
M	166 - 169	90 - 97
L	169 - 172	98 - 107
XL	172 - 178	108 - 119

Figure 7.21: X-Bionic size chart for women's compression tops (X-Bionic, 2016)

The size chart for women’s compression tops by Intelliskin (Table 7.21) took a different approach, incorporating weight instead of height into the size chart. The key dimensions of the size chart were chest, waist, hip and under bust girths as well as weight. When taking all of the body dimensions into account, none of the WT participants matched the criteria for the size designations.

Table 7.21: IntelliSkin size chart for women’s compression tops (measurements converted from inches to cm for length measurements and lbs to kg for weight) (IntelliSkin, 2017)

Size	Chest	Waist	Hip	Under bust	Weight
XS	71-81	61-66	86-91	71-76	41-50
S	76-86	66-71	91-97	76-81	48-59
M	86-97	71-81	97-102	81-91	57-66
L	91-102	81-86	102-112	91-97	64-75
XL	91-112	86-97	112-117	97-102	73-82
XXL	102-117	-	-	102-112+	79-91

The findings from the post-WT size chart assessment show that the size charts combining height and/or weight with body circumference measurements of the three SCG brands were not suitable for the WT participants. Whilst the WT participants were not a representative sample of active females, it is a concern that the majority of WT participants did not match the provided body dimensions for any of the size categories. Further research is needed on suitable sizing systems for SGCs that allow for accurate fit and reliable compression across different sizes.

7.5 Chapter Conclusions

The chapter has presented the findings from the Fabric Analysis, Garment Analysis and Size Chart Review of commercial women's SCGs.

The fabric analysis reported and compared the key properties of the fabrics used for SCGs and identified properties needed for the subsequent simulation study. Problems with residual extension were identified for the main fabric of the SCGs. The findings of the fabric analysis showed that it is important to consider that two different SCGs that appear to be similar, can vary widely in fabric properties, which can affect pressure application. Further, fabric placement on the body is critical, as fabric properties vary substantially in course and wale direction. However, due to the complicated structures of fabrics and their fibre, yarn and construction properties, it is not yet understood how specific variations in fabric properties translate to pressure levels.

The design and construction of the Skins SCGs were analysed in detail and the garments were re-engineered. The design of SCGs varies from conventional sportswear as they were designed to support key muscle groups. This resulted in more garment panels in the case of the Skins A400 SCGs. The garments also featured specifically developed seams.

The analysis of pressures applied by the SCGs to mannequins showed that pressures were distributed fairly gradually with highest pressures at the hems and lowest pressures at the torso. The different measuring conditions did not have significant effects on pressure levels with the only significant difference identified in size S between the 'after WTs' and 'after 5 washes' conditions.

Different sizing approaches by different SCG brands were identified particularly for lower-body garments. The sizing system applied for the Skins A400 compression tights followed a BMI sizing approach. A sizing system based only on height and weight without considerations of body circumference is problematic for compression sportswear, as it results in a wide range of leg circumferences within each size category. The Skins A400 size chart for compression tops was based on the chest circumference as primary dimension. This could result in problematic fit of the compression top, as waist or hip girths, which are commonly included in conventional sportswear sizing, were ignored.

The SCG size charts combining weight and/or height with circumference measurements assessed as part of the size chart review were identified to be inappropriate. The main problem lay in the assumptions that height increases linearly with increasing circumference measurements. The inclusion of limb circumferences could be beneficial for compression sportswear due to the link between pressure and limb circumferences (Laplace's Law). Further research is needed to identify suitable sizing systems for SCGs.

Overall, the design of SCGs varies from conventional sportswear design, as the ultimate goal of the design is the application of specific pressure levels at certain locations across the body. As such, every garment element needs to be selected and/or designed for optimal fit and pressure application.

8 FINDINGS FROM PHASE II – STUDY 3: SPORTS COMPRESSION GARMENTS AND THE HUMAN BODY

8.1 Chapter Introduction

This chapter focuses on the findings of Phase II – Study 3: Sports Compression Garments (SCGs) and the Human Body. After analysing SCG users (Study 1) and SCGs (Study 2) individually, Study 3 was concerned with the relationship between SCGs and wearers' bodies. The chapter presents and discusses the findings of wearer trials (WTs) with 33 female participants, fulfilling Aim 4 of the research project.

8.2 Objectives of Wearer Trials

The objectives of the WTs were:

1. To analyse the body dimensions of the WT participants and obtain body avatars that can be used for virtual fit.
2. To evaluate how the SCGs under investigation fit the WT participants' bodies.
3. To explore the WT participants' perceptions and evaluation of the SCGs in terms of design, fit, comfort and compression.
4. To quantify pressures applied by the SCGs to the WT participants' bodies.
5. To identify whether there are any relationships between body dimensions, pressure levels and fit that could support the prediction of pressures applied by SCGs.

8.3 Participants

The 33 female participants had a mean age of 31.0 years (*SD* ± 8.57) and were physically active with an average of 7.0 (*SD* ± 3.79) hours of exercise per week. The participants' mean key body measurements are shown in Table 8.1. The participants' mean BMI of 23.6 (*SD* ±2.84) was within the healthy range (National Health Service, 2015).

Table 8.1: Key body dimensions of wearer trial participants

Key body measurement	*N* = 33	
	Mean	**SD**
Height (cm)	165.47	6.54
Weight (kg)	64.50	7.03
BMI	23.58	2.84
Chest circumference (cm)	93.42	7.01
Waist circumference (cm)	89.51	6.54
Hip circumference (cm)	103.29	5.29

The chest circumference was used to classify participants into size categories for the compression top using the Skins A400 size chart, whilst height and weight measurements were mapped onto the Skins A400 size chart for compression tights as shown in Figure 8.1.

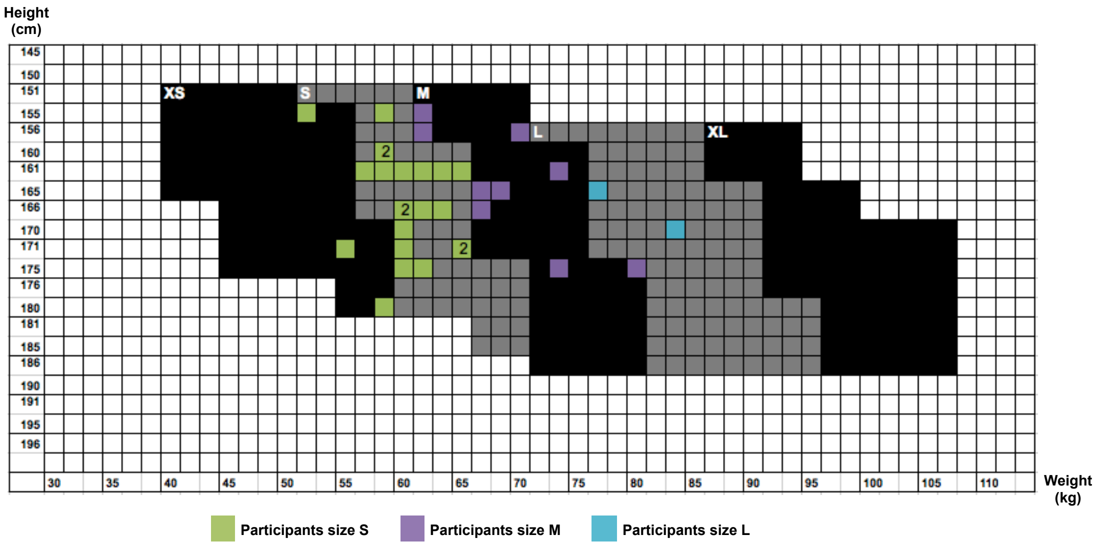


Figure 8.1: Spread of wearer trial participants on Skins size chart

8.4 Anthropometric Analysis

8.4.1 Findings of Anthropometric Analysis

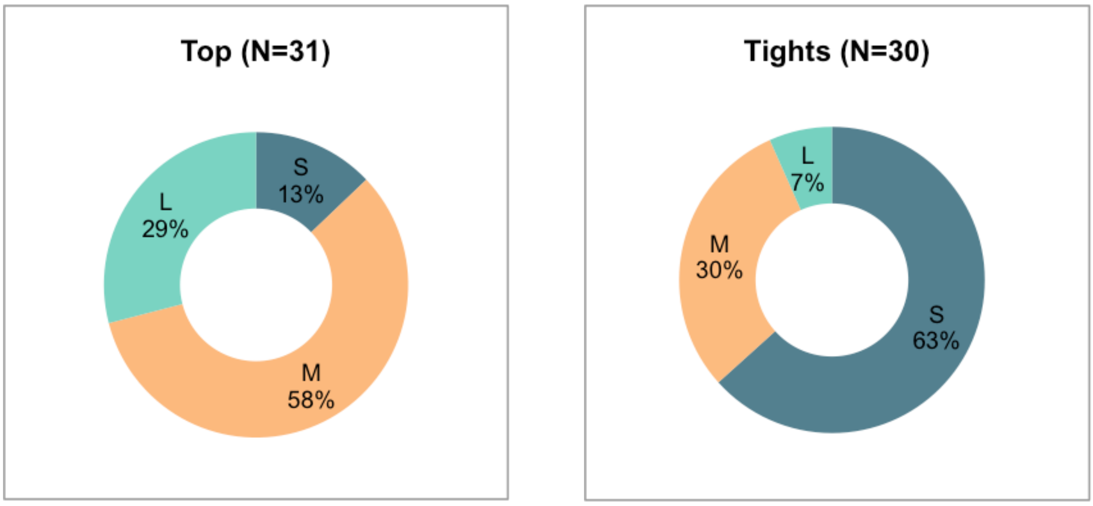
The anthropometric data discussed in this section are available in Appendix HH.

8.4.1.1 Body Measurements and Size Classification

The WT participants' body measurements were captured using a three dimensional (3D) body scanner (Size Stream, Cary, NC, USA). The key characteristics and body measurements extracted from the cleaned body scans of the 33 WT participants are presented in Appendix Table HH-1.

Three participants were allocated compression tights in size S even though they were classed as XS according to the Skins A400 size chart, as SCGs were only available in sizes S, M and L during the WTs. There were also two participants who were classed as size XL in the compression top based on their chest circumference, but were allocated a top in size L. This was a problem, as oversized tights and undersized tops could skew pressure results. Mann-Whitney tests were conducted (refer Appendix Table HH-2) to test whether there was a statistically significant difference between body measurements of participants classed as size S and XS in the tights as well as between participants classed L and XL in the top. The results of the Mann-Whitney tests revealed that there were statistically significant differences in many body dimensions including all torso circumference measurements of the participants classed size S in the tights and the ones classed XS. The Mann-Whitney tests for the compression top (refer Appendix Table HH-3) indicated that the chest circumference of the participants classed XL was significantly different to the participants classed size L (U = 0, p = 0.034, r = -0.64). There were no significant differences between any of the other body measurements of the participants classed size L and XL in the compression top. Based on these results, the three participants classed XS in the compression tights and the two participants classed XL in the compression top were eliminated from the subsequent analyses.

The mean key body measurements of the participants included in the data analysis of WT results for the compression tights (n = 30) and for the compression top (n = 31) are presented in Appendix Table HH-4. The size distribution across the WT participants was fairly uneven (refer Figure 8.2) with the majority of participants wearing size S in the compression tights (n = 22) and size M in the compression top (n = 18). Only two participants wore size L in the compression tights and only four wore size S in the compression top.



a) b)

Figure 8.2: Distribution of sizes in wearer trials for compression top (a) and tights (b)

Kruskal-Wallis tests revealed that there were no significant differences in body measurements across the different age groups (<24, 24-29, 30-39, ≥40) of the WT participants with exception of arm length for the compression top sample (H = 7.84, df = 3, p = 0.49). Mann-Whitney tests with Bonferroni correction (p < 0.0083) were used to follow up this finding. They identified that arm length only differed between age categories <24 and 30-39 (U = 8.00, p = 0.008, r = -0.64), but not between any of the other categories.

No statistically significant differences in body measurements could be identified between participants who train varying hours per week (>5, 5-9, ≥10) or participate in different types of sports (cardio, resistance, low impact, mixed cardio and resistance) using Kruskal-Wallis tests.

There were strong correlations between the height and inseam length (ρ_{tights} = 0.811; ρ_{top} = 0.823), the chest and waist girths (ρ_{tights} = 0.802; ρ_{top} = 0.818) and a very strong correlation between hip and seat girths (ρ_{tights} = 0.971; ρ_{top} = 0.971). Under consideration of the size chart for the compression tights, it was interesting to examine correlations between the BMI and lower body circumference measurements. There were strong correlations between the BMI and waist girth (ρ = 0.754), hip girth (ρ = 0.758) and seat girth (ρ = 0.778), whilst correlations between the BMI and mid-thigh (ρ = 0.503) or calf (ρ = 0.561) girths were moderate. There were no correlations between BMI and knee (ρ = 0.440) or ankle (ρ = 0.080) girths.

Some SCG brands had based their size charts for compression tights on thigh circumference measurements (refer 7.4.4). There was a moderate correlation between mid-thigh circumference and the following body measurements: hip girth (ρ = 0.643), seat girth (ρ = 0.603), knee girth (ρ = 0.670) and calf girth (ρ = 0.650).

The chest circumference was the determining body dimension for the sizing of the compression top. Spearman's correlations indicated that there was a moderate correlation between the chest and biceps girths (ρ = 0.639), but no correlations between chest girth and forearm girth (ρ = 0.417), wrist girth (ρ = 0.263) or arm length (ρ = -0.035).

8.4.1.2 Analysis of Body Measurements by Size

The previous section analysed the anthropometric data of the WT participants without consideration of size classifications. It is of particular interest to this study to analyse body measurements within the relevant size categories of the compression tights and top. Appendix Table HH-5 and Appendix Table HH-6 show the key body measurements of the participants within each size category of the compression tights and top. Comparing variations in body measurements is especially interesting for the compression tights since the size chart is not based on any circumference measurements, which are generally critical for garment sizing and fit (refer 3.3.6).

All mean circumference measurements of participants classed as size M in the compression tights were larger than the circumference measurements of participants classed as size S. The same was true for participants classed size L compared to size M with the exception of the ankle circumference, however, size L was limited by a small sample size (n = 2).

Waist circumference measurements increased with increasing size for the compression tops and, thus, with increasing chest circumference. There was only a small increase (0.14cm) in hip girth between sizes S and M of the compression top. The same could be observed for biceps (0.51cm) and wrist girths (0.03cm); however, forearm circumference slightly decreased from size S to M. There was also only a small increase in arm length between sizes M and L (0.28cm).

T-tests of the body measurements across sizes S and M of the compression tights were conducted as the lower body measurements relevant to the sizing of compression tights were all normally distributed. Size L was ignored in the statistical analysis due to the small sample size (n = 2). The t-test revealed that there were statistically significant differences between all body measurements except height, inseam length and ankle circumference (refer Appendix Table HH-7). These results indicate that length measurements as well as girth measurements at more bony body parts, such as the ankle, do not necessarily increase with an increase in size.

Kruskal-Wallis tests revealed that there were significant differences in all upper body measurements across the three size categories (S, M and L) of the compression top with exception of height, arm length and wrist circumference (refer Appendix Table HH-8). Post-hoc Mann-Whitney tests with Bonferroni correction (p < 0.017) were conducted to identify differences between the individual size categories. The only body measurement with statistically significant differences between sizes S and M was chest girth. All upper body measurements between sizes M and L were significantly different. The same was true for sizes S and L with the exception of forearm circumference.

Using the 3D body scanner software (Size Stream Studio), it was possible to extract body volumes. The different body volumes of WT participants within the different size categories were analysed (see Appendix Table HH-9). As would be expected, all body volume measurements increased with increasing size. There was a significant difference in body volume across different sizes of the compression tights (H (df = 2) = 17.95, p < 0.001). Post hoc Mann–Whitney tests with Bonferroni correction (p = 0.017) revealed that body volume was not significantly different between sizes S and L (U = 0, p = 0.023, r = −0.50) or M and L (U = 1, p = 0.059, r = -0.57). However, body volume was significantly different between sizes S and M (U = 8, p < 0.001, r = −0.72). This could be related to the small sample size of size L (n = 2). There was also a significant difference in body volume across different sizes of the compression top (H (df = 2) = 17.48, p < 0.001). The post hoc Mann–Whitney tests with Bonferroni correction indicated that body volume was not significantly different between sizes S and M (U = 9, p = 0.022, r = −0.49). However, body volume was significantly different between sizes S and L (U = 0, p = 0.005, r = -0.77) or M and L (U = 12, p < 0.001, r = −0.68). Whilst statistically significant differences could be identified between torso volumes of all sizes of the compression top (S-M: U = 6, p = 0.011, r = −0.54; S-L:

$U = 0$, $p = 0.005$, $r = -0.84$; M-L: $U = 9$, $p < 0.001$, $r = -0.71$), it appeared that bust volume was not significantly different between sizes S and M ($U = 26$, $p = 0.395$, $r = -0.18$). However, bust volume was significantly different between sizes S and L ($U = 0$, $p = 0.005$, $r = -0.77$) or M and L ($U = 18$, $p = 0.009$, $r = -0.50$). There were no statistically significant differences between right leg volumes of the different sizes of the compression tights (H ($df = 2$) = 5.67, $p = 0.059$). The lack of significant differences in body volumes between sizes S and M for the top goes in line with the lack of differences in body dimensions. Interestingly, there was a significant difference in chest circumference, but not in bust volume between sizes S and M. This reinforces the fact that circumference measurements cannot provide any information about body mass distribution across the front and back of the body.

Appendix Table HH-10 shows photographs of the lower bodies of participants with the minimum and maximum measurements of hip girth and mid-thigh girth for sizes S and M as well as photographs of the upper bodies of the minimum and maximum waist girth measurements for size S, M and L of the compression top. Size L of the tights was neglected due to the small sample size ($n = 2$). The photographs highlight the large variations in body dimensions, volume and composition. This is particularly obvious for size S of the compression tights.

8.4.1.3 Body Shape Classification

The participants' varying body dimensions warranted an analysis of the participants' body shapes. Considerations of different body shapes in the design of SCGs could potentially lead to improved fit and compression levels. The WT participants were categorised into different body shapes using a combination of established body shape classification techniques from literature as described in section 4.4.3.3. Table 8.2 shows the distribution of body shape categories for each of the three body shape classification systems applied as well as the final body shape classification for all 33 participants, for the compression tights sample and for the compression top sample. Participants classed as the same body shape by at least two systems were categorised as that particular body shape. The remaining body shapes were visually assessed and it was decided which of the identified body shape categories was a better fit. The vast majority of participants were classed as triangle shapes. Triangle or spoon shapes are characterised by being larger below the waist and smaller above the waist (Rasband and Liechty, 2006). A visual overview of the different body shapes can be found in Appendix II.

Table 8.2: Body shape categorisation of the wearer trial participants

	Triangle/ Spoon	Inverted triangle	Hourglass	Rectangle	Apple/ Diamond	None
Makhanya et al., 2014 (*N*=33)	21	2	8	2	0	0
Gribbin, 2014 (*N*=33)	26	0	0	5	N/A	2
Rasband and Liechty, 2006 (*N*=33)	27	1	0	4	0	1
Final (*N*=33)	24	2	6	1	0	0
Final – Tights (*n*=30)	22	2	5	1	0	0
Final – Top (*n*=31)	23	1	6	1	0	0

Most WT participants wore a smaller size in the compression tights compared to the compression top. In fact, all participants who had the same size in the compression tights and top based on the Skins size chart, were classified as triangle body shapes. The Skins size charts were seemingly most suitable for triangle body shapes. This could be related to the fact that the size chart of the tights was fairly generous, whilst the size chart of the top was more true to size.

Because such a large proportion of WT participants was classed as triangle shapes, Mann-Whitney tests were run to test whether there were statistically significant differences between the mean body measurements of triangles and the rest of the participants. There was a statistically significant difference in mean chest circumference ($U = 37$, $p = 0.004$, $r = -0.53$) between the participants that were classed as triangle shapes and the ones that were not for both the compression tights and top sample. There was also a statistically significant difference in mean under bust circumference ($U = 47$, $p = 0.013$, $r = -0.45$) for the compression tights sample. However, there was no significant difference in any of the other body measurements.

There was a statistically significant difference in age between the participants that were classed as triangle shapes and the ones that were not. The mean age of the triangle shapes was significantly lower ($M = 28.6 \pm 6.9$ (SD)) than the remaining participants ($M = 35.3 \pm 9.8$ (SD)). However, there was no significant difference between training hours, height, weight or BMI of the triangles and the remaining participants. No statistically significant differences between any of the body volumes and body shapes could be identified. Overall, triangles were younger and had smaller chest circumferences than the remaining WT participants.

8.4.1.4 Slices

During the colour 3D body scans, tape markers were attached to the outside of the SCGs worn by the WT participants. They were used to identify the pressure measurement (PM) locations and to extract slices of the body at these locations using the Size Steam Studio software. Not all tape markers could be identified on the colour scans, however, it was possible to extract slices of all participants at PM location B6 (gluteus maximus at biggest projection) and slices from 32 participants could be extracted at PM location B3 (calf at maximum girth). The mean measurements for each size designation are presented in Table 8.3.

Table 8.3: Mean circumference measurements extracted from slices of right leg

	Size	*n*	Range	Mean	*SD*
Circumference at B6	S	19	15.36	99.12	3.95
	M	9	7.72	103.63	2.78
	L	2	3.02	109.58	2.14
Circumference at B3	S	18	6.38	37.03	1.98
	M	9	4.63	39.71	1.62
	L	2	1.32	40.02	0.93

A Kruskal-Wallis test revealed that there were significant differences in circumferences at B6 across the different sizes (H (df = 2) = 12.16, p = 0.002). Follow-up Mann-Whitney tests with Bonferroni correction ($p < 0.017$) indicated that there was a significant difference in circumferences at B6 between sizes S and M (U = 29, p = 0.004, r = -0.53), but not between sizes S and L (U = 0, p = 0.023) or M and L (U = 0, p = 0.034). This could again be related to the small sample size of size L (n = 2). A further Kruskal-Wallis test revealed that there were significant differences in circumferences at B3 (H (df = 2) = 9.77, p = 0.008). Follow-up Mann-Whitney tests with Bonferroni correction ($p < 0.017$) indicated that there was a significant difference in B3 circumference between sizes S and M (U = 27, p = 0.005, r = -0.53), but not between sizes S and L (U = 3, p = 0.059) or M and L (U = 7, p = 0.637).

There were moderate correlations between the size of tights and the circumferences at B6 ($\rho = 0.64$, $p < 0.001$) and B3 ($\rho = 0.59$, $p = 0.001$).

8.4.1.5 Body - Garment

To get an indication of the amount of stretch of the fabric of the SCGs at different parts of the body, the garment stretch percentage was calculated based on the WT participants' body measurements and the garment flat measurements. The mean garment stretch measurements are presented in Table 8.4 and Table 8.5.

Table 8.4: Mean garment stretch of compression tights

Tights (n = 30)	Mean garment stretch (%)		
	S	M	L
Waist	35.96	32.19	35.04
Hip	60.27	50.45	44.92
Mid-thigh	38.27	33.73	36.46
Knee	56.72	56.05	64.89
Calf	72.24	72.86	64.70
Ankle	37.34	35.96	29.56

Table 8.5: Mean garment stretch of compression top

Top (n = 31)	Mean garment stretch (%)		
	S	M	L
Chest	30.55	31.04	31.85
Waist	44.58	43.09	44.31
Hip	54.89	47.01	43.97
Biceps	6.61	-0.32	1.18
Forearm	38.23	21.54	18.74
Wrist	23.18	13.29	11.83

There was a high variation of stretch levels across different body parts. The lowest mean stretch value for the compression tights was 29.56% in size L at the ankle, whilst the highest mean stretch value was 72.86% in size M at the calf. For the compression top, the lowest stretch value was -0.32% at the biceps in size M and the highest value was 54.89% at the hip in size S. The negative value of garment stretch at the biceps in size M was the result of the sleeve being slightly bigger (0.1cm) than the average biceps girth. It can be assumed that there would be no pressure applied to the biceps. There were large variations in garment stretch values across individuals within each size category for the compression tights and top with the exception of the chest and waist in size S for the top, where differences were below 5%. As was to be expected, variations in garment stretch were related to variations in girth measurements. Calf measurements in size S, which showed high variations in body measurements, resulted in garment stretch ranging from 54.35% to 84.44%. The lowest mean garment stretch values of below 40% were identified at the ankle, mid-thigh and waist for the compression tights and at the biceps, wrist, forearm and chest for the compression top. Stretch levels decreased from calf to mid-thigh across the leg for sizes S and M, whilst limb circumferences increased. The stretch levels at the sleeves increased from wrist to forearm, but there was a considerable drop in garment stretch at the biceps.

Spearman correlations were run to examine the relationship between body measurements and garment flat measurements (refer Appendix Table HH-11 and Appendix Table HH-12). Strong, significant correlations were detected at the calf for the compression tights (ρ = 0.74, p < 0.001) and at the chest for the compression top (ρ = 0.86, p < 0.001). There were no correlations in length measurements. The garment stretch percentage values were relatively even across sizes for most body locations, except for the hip. Garment stretch percentage values were also lower at the legs in size L and the sleeves in size S, however this could relate to the small sample size of these size categories. When considering pressure application, an equal garment stretch percentage level might not be the most desirable across sizes, as larger circumferences require larger fabric tension than smaller circumferences to achieve the same pressure delivery (Laplace's Law).

8.4.1.6 Differences in Body Measurements When Wearing SCGs

The extracted body measurements of the WT participants in underwear were compared to the measurements with SCGs. There were no substantial differences in body measurements with or without compression with variations lying within ±5% of the non-SCG scans, except for the measurements shown in Table 8.6. These values show that the ankle circumference was bigger when the participants wore the compression tights. This was likely caused by fit issues of the SCGs, as the leg length was too long for several participants and thus bunched up at the ankle. There was also an increase in the across back measurement, which could be related to variations in posture caused by wearing the compression top.

However, no clear conclusions can be drawn, as the underarm points were not always detected accurately by the body scanner due to 'webbing' in the underarm area and thus inaccuracies in measurements cannot be ruled out. The chest circumference, where tissue is very soft and compressible, was only reduced by 0.3%. However, the bust-to-bust length was reduced by 6.9%, whilst the volume of the right bust was reduced by 14.2% when wearing the compression top.

Table 8.6: Variations in body measurements when wearing compression garments

	Body measurement	Percentage change with SCG
Tights	Ankle circumference right	5.81%
Top	Across back	5.40%
	Bust to bust length	-6.86%
	Bust volume right	-14.24%

It was further examined whether there were correlations between body volumes and garment stretch values. Spearman's rho revealed moderate correlations between the right leg volume and garment stretch at the mid-thigh ($\rho = 0.61$, $p < 0.001$) and knee ($\rho = 0.64$, $p < 0.001$).

All conclusions resulting from the anthropometric analysis are based on the analysed WT participants only and are limited by the accuracy of the body scanner. Sample sizes for some of the sizes were very small. Larger samples of body measurements will have to be analysed to make recommendations for sizing of SCGs for the general population.

8.5 Fit Assessment

8.5.1 Results of Fit Assessment

The photographs taken of the participants wearing the Skins A400 compression top and compression tights were used to visually assess the fit of the SCGs after the WTs. The fit assessment applied the developed fit assessment score table (refer Appendix U). The fit assessment was done separately for the compression tights and tops. The summarised results of the fit assessment are presented in Appendix JJ.

The results showed that the compression tights were too long for almost half (46.6%) of the 30 participants, whilst the length was just right for 33.3% and too short for 20% of participants. Seam positioning seemed to be adequate for the tights, however, the positioning of the knee panel varied slightly based on problems with the leg length. As a result of the length issues, the fit of the compression tights at the ankles was unsatisfactory for a third of participants, as the excess fabric created fabric folds and creases at the ankles. For 70.1% of participants the waistband of the compression tights was too tight, but the fit across the legs and at the crotch was adequate.

The length of the compression top was satisfactory for most participants (71%), however, the sleeves were too long for 71% of participants. This caused fit problems at the lower sleeves with unsatisfactory fit for 61.3% of participants. There were also unsatisfactory fabric folds at the upper sleeves in 29.1% of cases. There were no fit problems at the front of the torso, however, for 67.7% of participants the fit at the back was unsatisfactory due to fabric folds and creases.

No strong correlations could be detected between body measurements and the fit assessment criteria using Spearman correlation tests (refer Appendix Table JJ-3). Kruskall-Wallis tests were conducted to detect any differences in fit assessment ratings across different garment sizes and body shapes (refer Appendix Table JJ-4 and Appendix Table JJ-5). There were no differences in overall fit ratings of the compression tights or top for different garment sizes (tights: H (df = 2) = 0.105, p = 0.949; top: H (df = 2) = 3.670, p = 0.160) or body shapes (tights: H (df = 3) = 1.814, p = 0.612; top: H (df = 3) = 3.904, p = 0.272). Further, no significant differences could be detected for the length of tights, torso or sleeves, fabric folds at the ankle, torso or shoulder and tightness of the waistband.

8.5.2 Discussion of Fit Assessment

The main fit problems of the compression tights were related to the length of the tights and the width of the waistband. Whilst height was one of the key dimensions for the size chart, each size category encompassed a wide range of heights, so it was to be expected that problems with the length of the tights would occur. It would be useful to incorporate different length options (e.g. tall or petite) into the sizing system. Whilst this would increase the number of sizes on offer, which brands usually try to avoid, fit is paramount for SCGs and, thus, different sizing approaches with more size categories are necessary to improve fit. Problems with the tightness of the waistband occurred because the sizing system of the compression tights did not consider circumference measurements. Garment stretch at the waistband was fairly low compared to the rest of the tights, but the use of different, less elastic fabric and a strong elastic band at the front of the waistband made it tighter than the rest of the garment, leading to the waistband constricting the body.

The main fit problems of the compression top were related to the fit of the sleeves and at the lower back. The sleeves were too long for many participants and too loose around the upper arms. This observation goes in line with the garment stretch values at the biceps, which were vastly lower than at other locations of the body with there being no stretch in size M.

There were many fabric folds and creases at the back of the compression top. The shape of the bodice could be improved to better fit the female anatomy to avoid fabric folds at the lower back. The five participants with satisfactory fit at the back all wore size M. The size chart of the compression top was based on chest circumference only; using an additional or different key dimension for the size chart could improve fit.

8.6 Wearer Trial Questionnaire

8.6.1 Results of Wearer Trial Questionnaire

In order to get an understanding of how the objective measurements and observations of the behaviour of the Skins A400 compression tights and top translate to the subjective assessment of the wearers, a questionnaire focusing on the design, comfort, fit and compression levels of the SCGs was conducted.

Overall, the participants found the SCGs comfortable with 73.4% (n_{tights} = 22) and 77.4% (n_{top} = 24) rating the SCGs as ‘comfortable’ or ‘completely comfortable’. Only one participant stated that the SCGs were uncomfortable. 24 out of 30 (tights) respectively 31 (tights) participants did not experience any discomfort wearing the SCGs. Most of the remaining participants rated the level of discomfort as a low-medium (n_{tights} = 3, n_{top} = 5) with nobody rating it as high. Discomfort was mainly felt around the waist (n = 5) due to the tightness of the elasticated waistband of the compression tights. Three participants felt discomfort at the arms with one of them finding the sleeve hem too tight. One participant also felt discomfort around the shoulders, whilst another one felt that the length of the tights caused discomfort around the lower legs as the fabric bunched around the ankles.

More than three-quarters of participants (76.7%, n_{tights} = 23; 80.6%, n_{top} = 25) stated that they were able to move freely without restrictions whilst wearing the SCGs. The majority of the remaining participants (n_{tights} = 5, n_{top} = 4) stated that they were slightly restricted in movement, whilst one participant felt restricted in movement of the shoulder and another one felt much restricted in her knee movement.

Important considerations for the analysis of the SCG-body-relationship were fit and applied level of compression of the SCGs under investigation. The participants were asked to rate the overall fit and the level of compression of the tights and top. Most participants (43.3%) rated the fit of the compression tights as 'excellent' (refer Figure 8.3). None of the participants rated the fit of the tights as 'below average'. 19.4% of the participants rated the fit of the compression top as 'excellent'. The majority of participants (67.7%) rated the compression top as 'above average'. Only one participant rated the overall fit as 'below average'. Most of the perceived fit problems were related to the length of the sleeves (n = 6) and legs (n = 5), which were too long for many participants (with the exception of one participant who stated that they were too short), as well as the tightness of the elasticated waistband (n = 6). The height of the participants commenting on the fit problems caused by the length of the arms and legs ranged from 154.2 to 172cm. The Skins size chart is supposed to encompass a height range of 150 to 185cm.

There were also comments about fit problems in the underarm area (n = 3), shoulder area (n = 2) as well as the midsection at the front of the top (n = 1) and at the thighs and gluteus maximus (n = 1). There was no statistically significant association between the fit rating and body shape categories for the compression tights (χ^2 $(df = 6)$ = 4.39, p = 0.624) or top (χ^2 $(df = 9)$ = 11.22, p = 0.261) based on chi-square tests.

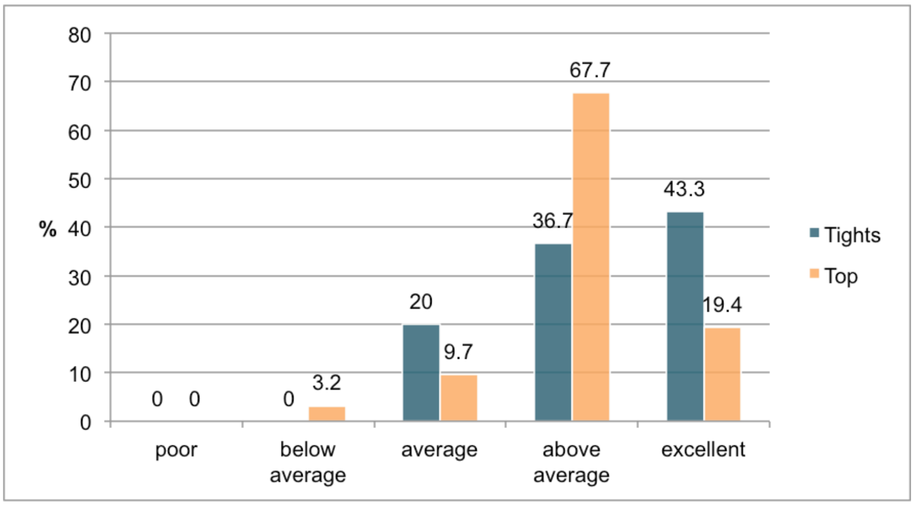


Figure 8.3: Level of perceived fit of compression tights and top

The level of compression of the top was rated as 'just right' by 64.5% of participants, whilst the compression level of the tights was rated as 'just right' by 86.7% of participants (refer Figure 8.4). 22.6% of participants rated the compression level of the top as 'too little', compared to 10% for the compression tights. The main problem areas in regard to compression levels mentioned by participants were the front midsection (*n* = 7) and the arms (*n* = 4). Two participants also felt that compression was 'too tight' in the underarm area, whilst one participant each stated that compression at the calves and thighs was 'too little'. Another participant stated that there was 'too much' pressure around the shoulders at the back.

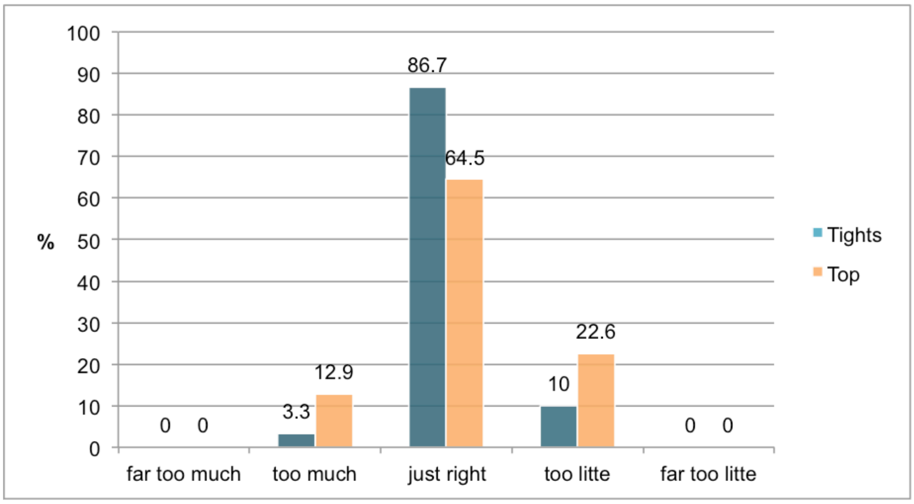


Figure 8.4: Level of perceived compression of compression tights and top

Chi-square tests were run to determine the association between participants' perceived level of compression and perceived level of fit of the compression tights and tops. There was no significant association between the level of perceived compression and level of perceived fit of the tights (χ^2 *(df = 4)* = 6.88, *p* = 0.143) or the tops (χ^2 *(df = 6)* = 8.56, *p* = 0.200). Further chi-square tests could not identify any associations between the participants' perceived fit and the results of the fit assessment reported in the previous section except for the association between the overall fit of the top and the rating of mean fabric folds at the torso as shown in Table 8.7.

Table 8.7: Chi-square test of association between perceived fit and visual fit assessment

Association		χ^2	*df*	*p*
WT questionnaire criterion	**Fit assessment criterion**			
Overall fit top	Mean length sleeve	11.04	18	0.893
Overall fit top	Mean folds upper sleeve	11.04	12	0.525
Overall fit top	Mean folds lower sleeve	12.73	12	0.389
Overall fit top	Mean folds torso	34.04	12	0.001*
Overall fit tights	Mean length tights	6.38	8	0.605
Overall fit tights	Mean folds ankles	4.85	6	0.564
Overall fit tights	Mean waistband fit	11.61	8	0.170

* significant association ($p < 0.01$)

The next-to-skin feel of the fabric used in the SCGs was perceived as 'above average' to 'excellent' by 97% of participants with 78.8% rating it as 'excellent'. The design of the SCGs also received overall positive ratings by the participants, with only 9% rating it as 'average' and 6% as 'below average'.

Only 45.5% of the participants stated that they would wear the compression top during their normal exercise routine in contrast to 72.7% of the participants who would wear the compression tights during exercise. Reasons for not wanting to wear the compression top were mainly related to habit or personal preferences (*n* = 9) and thermal considerations (*n* = 7). The participants commented that they prefer loose-fitting tops or do not usually wear long-sleeve tops. Some participants were concerned about overheating when wearing a long-sleeve compression top. Thermal considerations were also the main reason for participants not wanting to wear the compression tights (*n* = 3) as was habit or personal preference (*n* = 3). Another consideration was related to body image and being self-conscious as participants commented that they did not believe that a tight compression top would look flattering on them (n = 4), whilst one participant was concerned about showing all the "lumps and bumps" in compression tights. Some individuals also stated that they would wear the SCGs during recovery, if they fitted better or if they were less expensive. Mann-Whitney tests were run to assess whether there were significant differences in ratings of comfort between people who stated that they would wear SCGs and the ones who would not. No significant differences could be identified for the compression tights (U = 81.5, p = 0.247) or top (U = 127, p = 0.755).

42.4% of the WT participants stated that they would prefer to wear loose-fitting clothing over the SCGs (e.g. loose top (n = 14); shorts/skort (n = 7)), whilst 54.5% were happy to wear the SCGs as outer layer. More participants commented that they would wear a loose layer over the top than over the tights.

Less than half of the participants (45.5%, n = 15) believed in the performance-enhancing properties of SCGs, whilst 66.7% (n = 22) believed in their recovery-enhancing properties. However, it is important to consider that 48.5% of the participants never use SCGs during exercise, whilst 78.8% never wear them during recovery. More than half (56.3%) of participants who never wear SCGs during exercise (n = 16) did not believe that SCGs can improve performance, although 62.5% believed that they can enhance recovery. The majority of participants who frequently wear SCGs during exercise (n = 5) believed that SCGs positively affect performance and recovery (60% and 80% respectively). All participants (n = 3) who frequently wear SCGs during recovery believed that they positively affect performance and recovery.

Chi-square tests revealed that there were no associations between weekly training hours (<5, 5<10, ≥10) and participants' beliefs in performance- (χ^2 (df = 4) = 3.11, p = 0.539) or recovery-enhancing properties (χ^2 (df = 4) = 3.92, p = 0.417) of SCGs. There was further no association between the rating of the design of SCGs and people who believed in performance- (χ^2 (df = 6) = 5.01, p = 0.542) or recovery-enhancing properties (χ^2 (df = 6) = 2.54, p = 0.864) of SCGs and the ones who did not.

Participants were given the opportunity to comment on anything that they particularly liked or disliked about the SCGs. The responses were grouped and were related to five themes: design, wear/comfort, materials, wear perception and price as summarised in Figure 8.5. Most comments were related to the design of the garments. Several participants (*n* = 3) commented that they liked the non-slip silicone hem at the top, however, one participant commented that she did not like it. Three participants suggested more fashionable and colourful designs including prints, similar to the design of conventional sportswear. One of the comments was motivated by wanting to be trendier, whilst another one was more related to body image as the participant stated that a flashier design would distract from her body shape. Several participants pointed out the high level of comfort of the SCGs. There were also several positive comments about the material and its next-to-skin feel. A number of participants (*n* = 4) commented that they liked the feeling of being ‘squeezed in’ by the SCGs. One participant stated that she felt like a “ninja” wearing the garments. These comments indicate that SCGs can have a strong perceptual effect on wearers.

Design

- A more flashy design would be good to distract from the body shape.
- Would probably wear it more if CGs were available in trendier designs, like other sportswear
- Jazzier patterns and in tights would be nice
- Like the look of it (compared to old skins design)
- Don't like the paneling of the tights - it's not very flattering
- Like paneling
- Like the knee panels
- Like the waist level of tights, rather than hip level (no bulge)
- Top has good length
- Like neckline of top
- Top has flattering line around oblique
- Tights not flattering in front, especially because of the line in centre front (seam)
- Like that it's not pink or purple
- Nice colour
- Like reflective elements x2

Wear/comfort

- Like fit of top
- Like bottoms, but top feels too tight
- Ridges (seams) on arms and calves would annoy me
- Like the seams, they are silky
- Feels very warm
- Difficult to put on

Materials

- Like silicone grip at hem on top x3
- Don't like the use of silicone at hem of top
- Like the way material feels/soft x3
- Like thinner material than other brands (e.g. Canterbury)
- Material is not transparent/does not shine through, unlike 2XU
- Fabric feels very durable

Perception

- Like how muscles are kept tight
- Like the feeling of being tight
- Looks like it's looking after the body, seems to be doing the job, bit like strapping
- Feel like 'ninja'/out of bond movie

Price

- Would potentially buy them if they were not more expensive than other sportswear
- Too expensive

Figure 8.5: Comments by wearer trial participants about the Skins compression garments used in the wearer trials

8.6.2 Discussion of Wearer Trial Questionnaire Results

8.6.2.1 Comfort and Fit

Overall, the Skins A400 compression tights and top were perceived as positive in terms of comfort and next-to-skin feel by most WT participants. The majority of participants also liked the plain black design of the SCGs. However, there were problems with the length of the legs and sleeves of the compression tights and top and the tightness of the waistband for some participants causing fit issues and discomfort. It was surprising that the length of the compression tights was too long for some of the participants since the size chart used height as one of the key dimensions for size determination. The size chart was designed to include a height range of 150 to 185cm depending on the wearer's weight. Due to the limited number of sizes, each size category encompasses a large height range resulting in women of the same weight but with as much as 20cm difference in height having to fit the same sized tights. The size chart for compression tights by 2XU addresses this problem by offering tall options in the core sizes S, M and L, although even in the 2XU size chart (Figure 7.15) there is a wide height range in each size category as the tall sizes start at 176cm for size S and 180cm for size M and L.

The fit problems with the length of the sleeves and legs of the SCGs and the waistband were also identified in the visual fit assessment reported in the previous section. It was identified that the waistband was visibly constricting the waist and thus was too tight for 70.1% of participants during the fit assessment. There is a case for a re-design of size charts for SCGs with potential inclusion of girth measurements. Though, overall the fit of the compression tights was rated higher than the fit of the top. Whilst there was no association between fit ratings and the levels of compression, the better-perceived fit of the compression tights (43.3% 'excellent') compared to the top (19.4% 'excellent') resulted in more participants being satisfied with the levels of compression of the tights (86.7% 'just right') than the top (64.5% 'just right'). Some participants rated compression levels at the sleeves and the torso as too low.

There seemed to be a problem with the fit and grading of the sleeves of the compression top as problems with the fit of the sleeves were also identified in the fit assessment in the previous section and in the calculation of garment stretch. Although there was no direct link between the objective fit assessment of the participants and the visual fit assessment of sleeve length and fabric folds at the sleeves.

8.6.2.2 Overheating

This was the first study to detect wearers' concerns about overheating when wearing SCGs. The main fabric used in the SCGs showed very good moisture management properties (4.5 out of 5) when tested with the Moisture Management Tester in Study 2. This means that the fabric wicks sweat away from the body to keep the body dry and cool through evaporation. However, the participants did not necessarily have this technical knowledge believing that wearing long sleeves and tights could be detrimental to their performance. This finding highlights the need to promote the benefits of sportswear and technical fabrics to non-expert consumers. Thermal considerations were one of the reasons why the majority of participants would not wear the compression top during exercise. The participants were not used to wearing tight, long sleeve tops during exercise.

8.6.2.3 Recovery

The fact that more WT participants believed in the recovery-enhancing properties (66.7%) than performance-enhancing properties (45.5%) of SCGs goes in line with the findings from the online survey, which found that 49% of respondents who use SCGs (n = 145) believed in the performance-enhancing properties of SCGs, whereas 77.9% believed that SCGs improve recovery. The slightly higher numbers in the belief in SCGs of the survey respondents could be linked to the fact that the survey respondents were SCG users, whereas almost half of the WT participants (48.5%, n = 16) never use SCGs during exercise and 78.8% (n = 26) never use them during recovery. The online survey had found that the belief in performance- or recovery-enhancing properties of SCGs results in significant differences in attitudes towards SCGs and the way SCGs are used. In support of this finding, there was a relation between the belief in the SCGs' ability to improve performance and recovery and the wear frequency of SCGs during exercise or recovery by the WT participants.

8.6.2.4 Perception

The findings of the WT questionnaire show that SCGs can have a strong perceptual effect on wearers with some participants stating their positive feelings of wearing SCGs. This could potentially lead to improved sports performance. However, there was an element of self-consciousness in exercising with a tight compression top. Some participants commented that they feel self-conscious about wearing SCGs. Furthermore, more participants would prefer to wear additional, loose-fitting clothing over the compression top than the tights. This indicates that there was a bigger concern about exposing the upper body in skin-tight clothing during exercise than the lower body.

The preference for compression tights over compression tops goes in line with findings from the online survey conducted in Study 1, which showed that survey respondents mainly wore lower body SCGs with 74.3% of all SCGs mentioned by respondents being lower body garments. A higher percentage of WT participants (42.4%) would prefer to wear additional clothing over SCGs than female survey respondents (32.5%). However, it needs to be considered that most of the survey respondents were users of lower body SCGs.

SCGs can either have a positive, empowering perceptual effect on the wearer or make them feel uncomfortable, depending on the way they perceive their own bodies. Interestingly, the comments about positive feelings elicited from SCGs were made by slim participants with a BMI of less than 22 who were classed as size S in the compression tights and size S and M in the tops.

8.7 Pressure Analysis

8.7.1 Results of Pressure Analysis

The final part of Phase II - Study 3 was to measure the pressures applied by the SCGs to the WT participants' bodies. The results were analysed within the context of the results of the previous analyses, such as the participants' body measurements and their responses to the WT questionnaire, but also garment stretch measurements and pressure levels measured on mannequins from Study 2 (Chapter 7).

The PMs were analysed descriptively to identify mean pressure levels, pressure distributions across the body and any potential variations in applied pressure. The mean PMs recorded at each location in standing position are presented in Figure 8.6 for the compression tights and Figure 8.7 for the compression top.

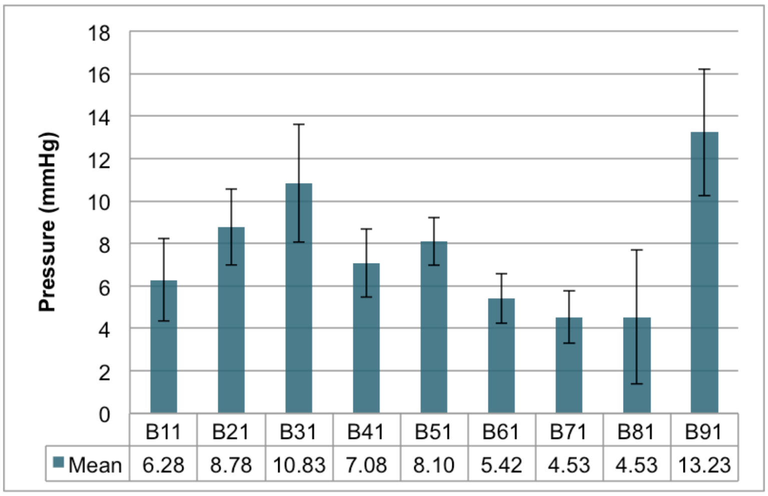


Figure 8.6: Mean pressures (±SD) measured on compression tights in standing position (Posture 1; *n* = 30)

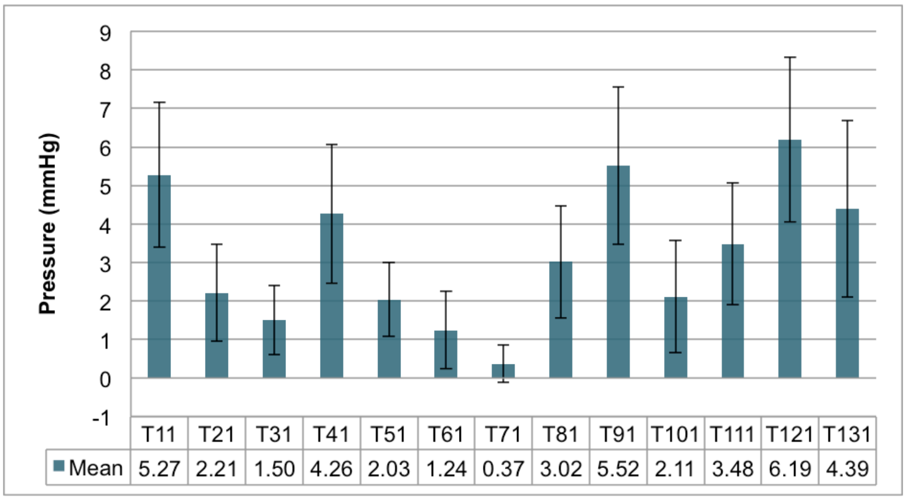


Figure 8.7: Mean pressures (±SD) measured on compression top in standing position (Posture 1; *n* = 31)

The overall mean pressure value measured on the compression tights in standing position was 7.6mmHg with recorded values ranging widely from 1 to 23mmHg. The highest pressure value was recorded at location B31 (calf at max. girth) in size Small. This value was recorded on a participant who was at the lower end of her size category (163.3cm, 57.1kg). Her calf circumference of 39.11cm was above the mean calf circumference of 37.06cm in this size category. The lowest pressure value measured at this measurement location was 7mmHg (size S – calf circumference: 33.06). These findings indicate a relationship between limb circumference and pressure values. The lowest pressure value recorded during the WTs on the tights was 1mmHg at location B81 (10cm below navel at centre front) in size M. This value was measured on a participant who sat in the centre of the size range for size M (163.3cm, 73.9kg). The maximum value measured at this location was 16mmHg for size S and 8.5mmHg for size M. B31 and B81 were the PM locations with the biggest variations across individuals with ranges of 16mmHg and 15mmHg, respectively.

The overall mean pressure measured on the compression top in standing position was, with 3.2mmHg, considerably lower than the mean pressure recorded on the tights. Pressure values ranged from 0 to 11mmHg. The highest pressure value recorded during the WTs on the compression top in standing position was 11mmHg at locations T41 (waist, size L) and T121 (forearm, size S). Both of the participants were right at the top edge of their respective size category. The lowest values recorded at these locations were 1.5mmHg for T41 (size M) and 2mmHg for T121 (size M). These measurements were taken on participants that were at the very low end of their size category, so there could be a relation between pressure values and sizing. T41 and T121 were the PM locations with the highest pressure variations across individuals with ranges of 9.5mmHg and 9mmHg, respectively. There were several locations across the upper body where pressure levels were 0mmHg: T3 (front oblique, size L), T6 (front chest muscle, all sizes), T7 (neckline at centre front, all sizes) and T10 (5cm down from shoulder at back, sizes M and L). Maximum values measured at these PM locations were 4, 4.5, 1, 1, 5, respectively.

There were no statistically significant differences in pressure levels at the compression tights or top across the different age groups (<24, 24-29, 30-39, ≥40) or groups of training frequency (<5h, 5-9h, ≥10h). However, there was a statistically significant difference in pressures across different types of sport at measurement location T31 (U = 39.5, p = 0.016, r = -0.45) between participants doing mainly cardio and the ones doing a mix of cardio and resistance training, even though there was no significant difference in body dimensions across participants engaging in different types of exercise.

The distribution of the mean pressure values across the body is visualised in Figure 8.8. It can be observed that the pressure gradually increased from ankle to calf, but then dropped at the knee with a small increase from knee to mid-thigh. Pressure levels across the seat and hip were considerably lower than pressure levels at the lower limbs, however, the highest level of pressure was elicited at the waistband. Across the upper body, pressure values were higher at the hem and waist compared to the rest of the mid-section. There was relatively high pressure at the top of the shoulder (T91). Pressure at the sleeves was not gradual. Pressure at the wrist (T131) was higher than at the biceps (T111) with the highest level at the forearm (T121).

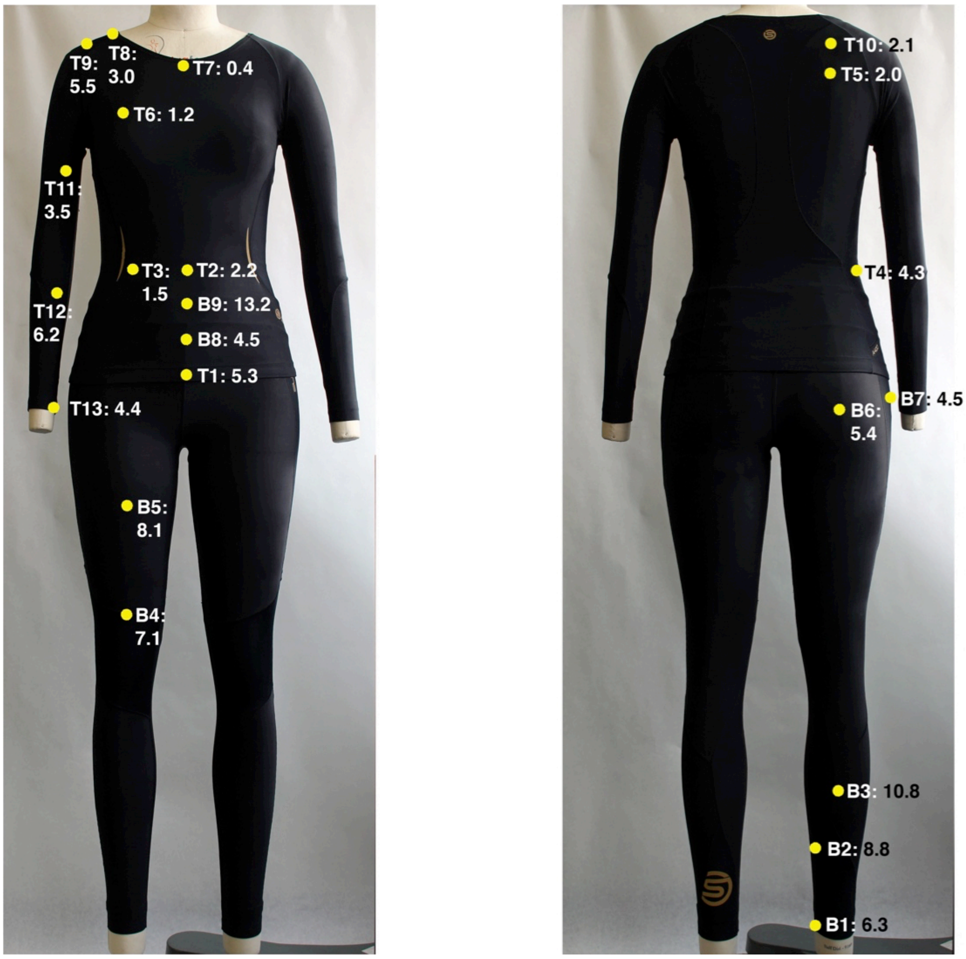
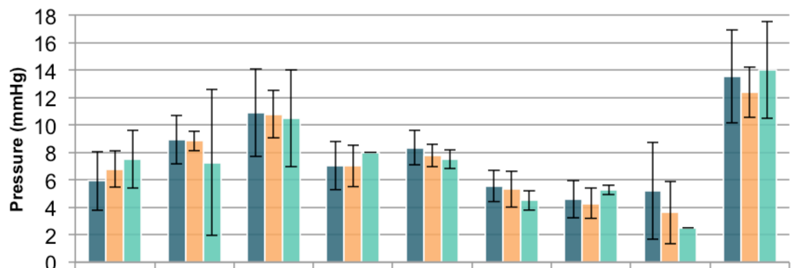


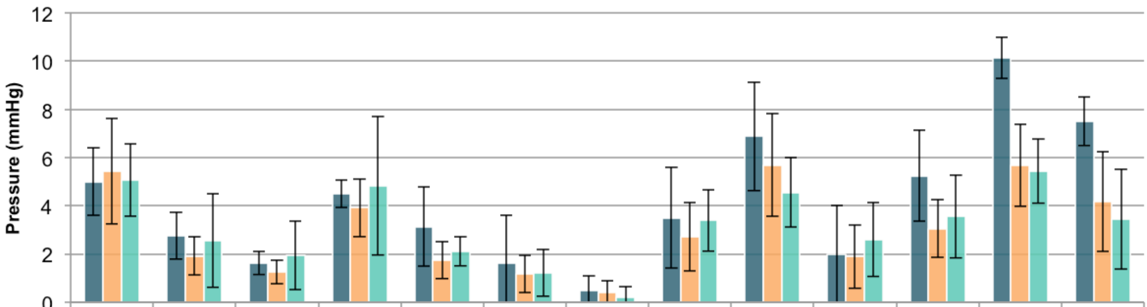
Figure 8.8: Mean pressure levels measured across the WT participants

Figure 8.9 and Figure 8.10 show the mean pressures applied by the compression tights and top at the different measurement locations on the wearers' bodies across the range of core sizes. The overall mean pressure measured on the compression tights was 8.4mmHg for size S, 8mmHg for size M and 7.9mmHg for size L. The total mean pressure for the Skins compression top was 4.6mmHg for size S, 3.3mmHg for size M and 3.5mmHg for size L.



	B11	B21	B31	B41	B51	B61	B71	B81	B91
S	5.92	8.92	10.9	7.0	8.3	5.6	4.6	5.2	13.6
M	6.78	8.83	10.8	7.0	7.8	5.3	4.3	3.6	12.4
L	7.5	7.25	10.5	8.0	7.5	4.5	5.3	2.5	14.0

Figure 8.9: Mean pressures (±SD) measured on the compression tights within each size category S, M and L in Posture 1 (*n* = 30)



	T11	T21	T31	T41	T51	T61	T71	T81	T91	T101	T111	T121	T131
S	5.0	2.8	1.6	4.5	3.1	1.6	0.5	3.5	6.9	2.0	5.3	10.1	7.5
M	5.4	1.9	1.3	3.9	1.8	1.2	0.4	2.7	5.7	1.9	3.1	5.7	4.2
L	5.1	2.6	1.9	4.8	2.1	1.2	0.2	3.4	4.6	2.6	3.6	5.4	3.4

Figure 8.10: Mean pressures (±SD) measured on the compression top within each size category S, M and L in Posture 1 (*n* = 31)

Kruskal-Wallis tests did not reveal any statistically significant differences in PMs in standing position across the range of sizes S, M and L of the compression tights. However, there were statistically significant differences across the three size categories for the compression top at PM locations T121 (H (df = 2) = 10.40, p = 0.006) and T131 (H (df = 2) = 8.31, p = 0.016). Mann-Whitney follow-up tests with Bonferroni correction ($p < 0.017$) revealed that there were significant differences in pressure levels between sizes S and M at T121 (U = 0.5, p = 0.002, r = -0.65) and T131 (U = 6.5, p = 0.011, r = -0.54), as well as between sizes S and L at T121 (U = 0, p = 0.005, r = -0.78) and T131 (U = 1.5, p = 0.010, r = -0.72). However, there were no statistically significant differences in pressure levels between sizes M and L at T121 and T131.

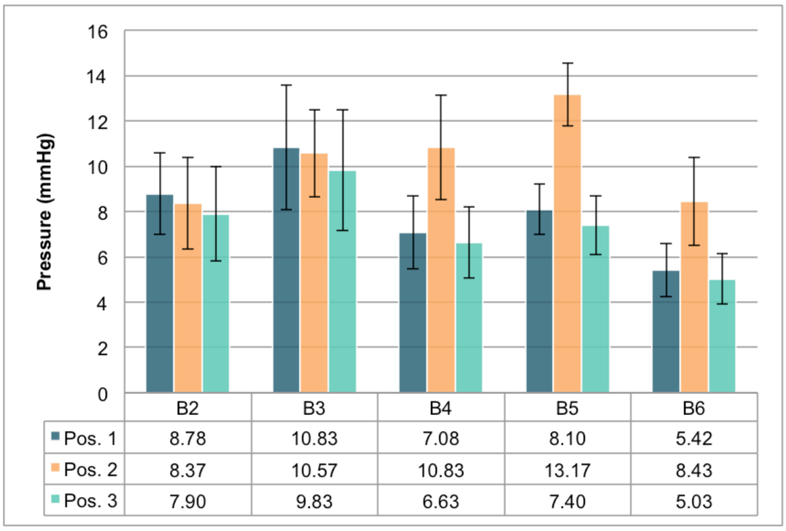
8.7.1.1 Pressure - Body

Spearman's rho correlations were applied to assess the relationships between body measurements and measured pressure values (refer Appendix Table KK-1). Due to the pressure variations across different sizes of the compression top, the correlations were analysed within the size categories for both the compression tights and top. There was a strong, positive correlation between the pressure at B61 and the seat circumference in size M for the compression tights (ρ = 0.829, p = 0.006). There was also a strong, positive correlation between pressure at T111 and biceps circumference (ρ = 0.891, p = 0.001) in size L of the compression top. There were no significant correlations between the other size categories.

Because the body circumference used in the above correlations do not necessarily reflect the exact PM locations, the slices taken at PM locations B3 (calf) and B6 (gluteus maximus) from the colour scans of the WT participants wearing the SCGs were also correlated with the PMs recorded at these locations using Spearman's rho. There were no significant correlations between slice circumference measurements and pressure values at B31 in size S (ρ = 0.33, p = 0.176) or size M (ρ = 0.51, p = 0.164). There were further no statistically significant correlations between slice circumferences and pressure levels at B61 in size S (ρ = 0.26, p = 0.290). However, there was a strong, positive monotonic correlation between circumference and pressure at B61 in size M of the compression tights (ρ = 0.83, p = 0.006). This result supports the detected correlation between the seat circumference and pressure at B61. These findings show that larger seat circumferences resulted in pressure increases at PM location B61 for the participants wearing the compression tights in size M.

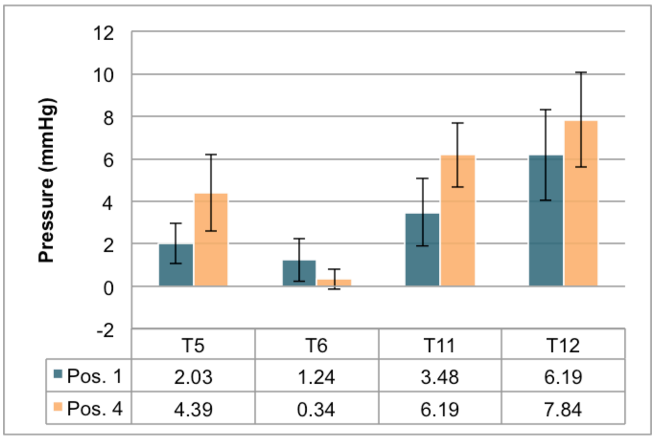
There were no significant correlations between weight, BMI and overall body volume of the WT participants and pressure values measured at the tights or top. There were further no significant correlations between the torso volume and torso PMs or right leg volume and PMs of the leg.

Pressure levels were recorded not only in standing position, but also in two additional postures (Postures 2 and 3) for five PM locations for the compression tights and in one additional posture (Posture 4) for four PM locations of the compression top (refer Appendix X for postures). One of the pressure values recorded at one participant at PM location T114 was a clear outlier. The researcher had made a note during the WTs that there was a measurement error, as it was suspected that the sensor was squeezed in the elbow crease when the participant moved into Posture 4. The value was 20mmHg, whilst the overall mean was 6.7mmHg. This outlier was replaced with the 5% trimmed mean value (5.94mmHg) for the respective size (Medium) as is recommended in literature (Pallant, 2013; Tabachnick and Fidell, 2013). The mean PMs recorded at these additional locations are presented in Figure 8.11 and Figure 8.12 together with the original results in standing posture (Posture 1) for comparative purposes.



	B2	B3	B4	B5	B6
Pos. 1	8.78	10.83	7.08	8.10	5.42
Pos. 2	8.37	10.57	10.83	13.17	8.43
Pos. 3	7.90	9.83	6.63	7.40	5.03

Figure 8.11: Mean pressures (±SD) of tights in different postures



	T5	T6	T11	T12
Pos. 1	2.03	1.24	3.48	6.19
Pos. 4	4.39	0.34	6.19	7.84

Figure 8.12: Mean pressures (±SD) of top in different postures

Wilcoxon signed-rank tests showed that pressure levels at locations B2, B4, B5 and B6 varied significantly when moving away from standing position into Posture 2 (leg lifted in front of body, knee bent to 90 degrees) and Posture 3 (tip toe stance). There was only a significant difference in pressure values between Posture 1 and 3 at the calf (B3), but no significant difference between Posture 1 and 2 (refer Table 8.8).

Table 8.8: Wilcoxon signed rank test: Differences in pressure applied by tights in different body postures

Measurement point - standing	Posture	*Z*	*p*	*r*
B21	2	-2.68	0.007*	-0.35
	3	-3.45	0.001*	-0.45
B31	2	-0.95	0.343	-0.12
	3	-2.89	0.004*	-0.37
B41	2	-4.80	<0.001*	-0.62
	3	-2.52	0.012**	-0.33
B51	2	-4.82	<0.001*	-0.62
	3	-3.83	<0.001*	-0.49
B61	2	-4.73	<0.001*	-0.61
	3	-3.13	0.002*	-0.40

*significant difference ($p < 0.01$)
**significant difference ($p < 0.05$)

For the compression top, Wilcoxon signed-rank tests revealed that pressure levels at locations T5, T6, T11 and T12 varied significantly when moving away from standing position into Posture 4 (arm lifted in front of body, elbow bent to 90 degrees), as reported in Table 8.9.

Table 8.9: Wilcoxon signed rank test: Differences in pressure applied by top in different body postures

Measurement point - standing	Posture	*Z*	*p*	*r*
T51	4	-4.73	<0.001*	-0.60
T61	4	-4.15	<0.001*	-0.53
T111	4	-4.80	<0.001*	-0.61
T121	4	-4.39	<0.001*	-0.56

*significant difference ($p < 0.01$)

In order to quantify the pressure variations, percentage variations were calculated from the pressure means. The results are reported in Table 8.10 for the compression tights and Table 8.11 for the compression tops.

Table 8.10: Percentage variations in pressure in different body postures for compression tights

Measure-ment point	Pressure (mmHg)			% change Pos. 1 to 2	% change Pos. 1 to 3
	Pos. 1	Pos. 2	Pos. 3		
B2	8.78	8.37	7.90	-4.67	-10.02
B3	10.83	10.57	9.83	-2.40	-9.23
B4	7.08	10.83	6.63	52.97	-6.36
B5	8.10	13.17	7.40	62.59	-8.64
B6	5.42	8.43	5.03	55.54	-7.20

Table 8.11: Percentage variations in pressure in different body postures for compression top

Measure-ment point	Pressure (mmHg)		% change Pos. 1 to 4
	Pos. 1	Pos. 4	
T5	2.03	4.39	116.26
T6	1.24	0.34	-72.58
T11	3.48	6.19	77.87
T12	6.19	7.84	26.66

The mean pressure levels applied by the compression tights in size S to the WT participants' bodies (n = 19) and to the mannequins (n = 4) are presented in Figure 8.13. Whilst the mean pressures applied to WT participants (n = 18) and mannequins (n = 4) by the compression top in size M are shown in Figure 8.14. Mann-Whitney tests were conducted to compare these pressure values. There were significant differences in pressure levels measured on participants and mannequins at measurement locations B11 (U = 0, p = 0.002, r = -0.65), B21 (U = 2.5, p = 0.004, r = -0.61), B41 (U = 0, p = 0.002, r = -0.46), B51 (U = 11.5, p = 0.027, r = -0.46) and B61 (U = 0, p = 0.002, r = -0.66) of the compression tights in size S. The mean pressures measured on the mannequins at these locations were significantly higher than the pressures measured on human bodies. There were also significant differences in pressure values measured on participants and mannequins at the top in size M at measurement locations T41 (U = 7, p = 0.011, r = -0.54), T71 (U = 3.5, p = 0.003, r = -0.64), T111 (U = 1, p = 0.003, r = -0.64) and T131 (U = 0, p = 0.002, r = -0.66). The mean pressures at PM locations T71, T111 and T131 were significantly higher on the mannequins than participants, whilst the pressure at T41 was higher on the human bodies.

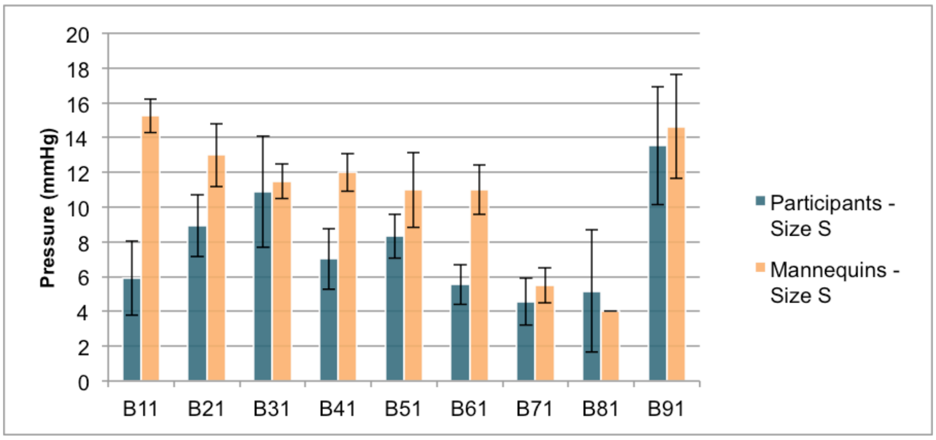


Figure 8.13: Mean pressures (±SD) applied by compression tights to participants and mannequins

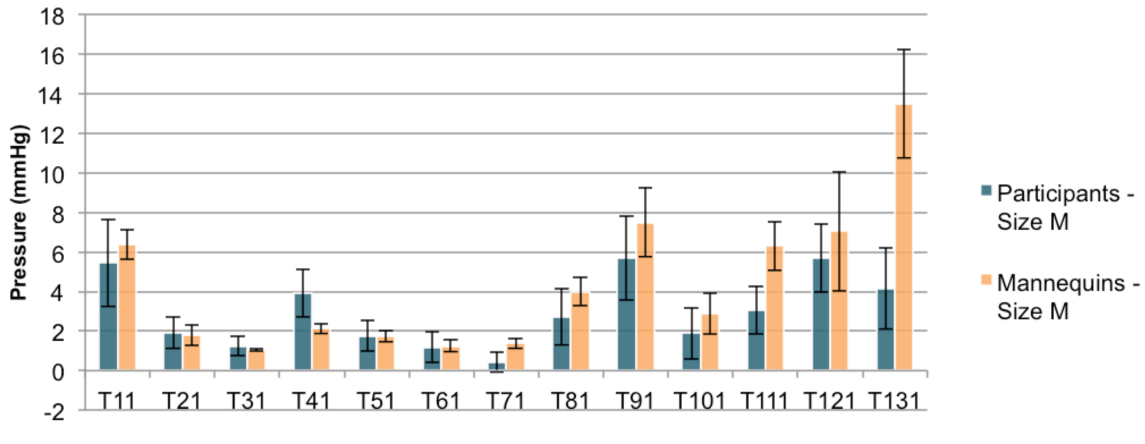


Figure 8.14: Mean pressures (±SD) applied by compression top to participants and mannequin

It is obvious from the bar charts in Figure 8.13 and Figure 8.14 that the pressure distribution across the body also varied across mannequins and WT participants. Skins market their SCGs as gradual SCGs. With gradual compression it would be expected that pressure levels are highest at the distal end of the limb and gradually decrease towards the heart (or the other way around). In this case, it would mean a gradual decrease in pressure from B11 (ankle) to B51 (mid-thigh). The mean pressure distribution of the mannequins is closer to this distribution pattern than the pressure distribution at the WT participants' bodies. When examining the pressure distribution at the sleeves of the top (T111, T121, T131), pressure gradually increases towards T131 (wrist) for the mannequins, but not for the WT participants.

The garment stretch percentage values that were calculated as part of the anthropometric analysis of this study were correlated to the pressure values recorded at the relevant PM locations for each size category of the compression tights and top as shown in Appendix Table KK-2. Significant, strong correlations could only be determined between pressure levels at B61 and garment stretch at the hip in size M of the tights (ρ = 0.82, p = 0.007) and between pressure levels at T111 and garment stretch at the biceps in size L of the top (ρ = 0.89, p = 0.001).

The responses of the WT questionnaire related to the perceived level of compression and fit of the SCGs were correlated to the in vivo pressure levels. There were no correlations between in vivo pressures and perceived level of compression or fit for the compression tights. Furthermore, no significant correlations could be detected between the in vivo PMs and the perceived level of fit of the compression top.

When examining some of the comments made by participants regarding the compression tights, it became evident that not all perceptions were reflected in the measured pressure levels. For instance, the pressure at the waistband (B91) of participants who reported that the waistband was too tight (n = 5), ranged from 8 to 15.5mmHg with the overall mean pressure being 13.2mmHg. So the perceived tightness was not necessarily related to the level of applied pressure, since participants with as much as 21mmHg did not comment about the tightness of the waistband. In contrast, the participants' perception of low compression levels around the torso (n = 6) was backed by the PMs at the different locations around the torso of these participants, which were very low ranging from 1 to 3mmHg at T21 and 0.5 to 2mmHg at T31. Although, one participant who commented that the level of compression at the midsection was too high received similar pressure levels (T21: 3mmHg, T31: 1mmHg) indicating that perceptions of compression can vary substantially across individuals.

8.7.2 Discussion of Pressure Analysis

It was important to interpret the reported results from the pressure analysis not just in isolation, but also within the context of the other finding of this study. The highest mean pressure of the compression tights was recorded at the waistband (B9: 13.2mmHg). With several participants commenting about discomfort induced by the tightness of the waistband and the visual fit assessment identifying the waistband as too tight for 70.1% of participants, it can be concluded that the waistband requires a re-design. It is further believed that there is no need for high pressure application at the waist due to its proximity to the heart and there not being any major muscle groups that would require support at the waist. Pressure levels at the waist could be expected to be similar to pressure levels at other locations of the lower torso (B7 and B8), since the characteristics of these locations are similar. With the garment stretch percentage being lower at the waistband than at other parts of the body (e.g. hip, knee), the fabric used for the back and sides of the waistband (Fabric B) was less extensible in cross-body direction than the main fabric used in the garment (Fabric A). The front of the waistband featured Fabric A covering a 39mm-wide elastic band. Perhaps the use of alternative, more stretchable materials could improve the comfort and pressure application at the waist.

It is difficult to comment on variations in pressure values across different fabrics, as the fabrics were placed at different parts of the body and the size and curvature of the body part below the fabric affect pressure levels. The tights featured two layers of fabric at the side of the upper thigh (Fabric C on the inside and Fabric D on the outside). The mean applied pressure at this point (B71) was 4.5mmHg, which was lower than the average pressure across all measuring locations, which was 7.6mmHg. The compression top featured panels of Fabric F at the side of the waist. The mean pressure measured at this location (T41) was 4.3mmHg, which was slightly above the overall average pressure of 3.2mmHg measured across all upper body locations.

Pressure levels at the top were generally lower compared to the compression tights. There was close to no mean pressure at the centre neckline (T71) and very low pressure at the chest muscle (T61), whereas the highest pressures were recorded at the forearm (T121) and top of the shoulder (T91). Whilst it could be argued that there is no need for a lot of pressure at the neckline, it could be of benefit to have compression at the chest muscle and the bust to provide support during movement. However, based on the female anatomy, the key contact points of the compression top were on top of the shoulder and at the bust point. The fabric was stretched between these points, resulting in low pressure at the neckline and chest muscle. This became even more apparent when the participants moved their arm into Posture 4. As the arm was lifted and moved forward with the elbow joint bent to a 90-degree angle, a concave formed between the shoulder and the front neck lifting the fabric away from the body surface. This resulted in an over 70% decrease in pressure at the chest muscle between Posture 1 and Posture 4. As the top of the shoulder (T91) was a key contact point of the compression top and the body, pressure at T91 was one of the highest values for the compression top.

Overall, measured pressure levels were fairly low, especially for the compression top, where there was no applied pressure at several PM locations for some WT participants. Even though an ‘optimal’ level of pressure for SCGs has not been determined yet, it is unlikely that average pressure values of 3.2mmHg of the top would have any physiological effects on the wearer. As comparison, pressure levels in existing literature generally ranged from 5 to 46mmHg, whilst medical compression levels range from 15 to over 49mmHg (Ramelet, 2002). Pressure levels measured at the tights were slightly higher and existing studies have found both positive and no effects of wearing compression tights with pressures as low as 5mmHg. Whilst existing research did not measure pressure at as many PM locations as this study and most only focused on either upper or lower body garments, there have been mixed findings in terms of pressure distribution. Some researchers (e.g. Sear et al., 2010) reported that the pressure distribution of compression tights was gradual, whilst others found that it was not (e.g. Brophy-Williams et al., 2015). The mean pressure level at the ankle (B11) was lower than pressure at the lower calf (B21) and calf (B31). SCGs with gradual compression would have the highest pressure level at the distal end of the limb, i.e. the ankle and wrist, with compression gradually decreasing towards the heart. Whilst the point measurements measured in this study cannot provide conclusive remarks about the gradual pressure distribution across the body, due to potential variations in pressure along circumferences, they can give indications of the designed pressure profile.

Reasons for lower pressure levels at the ankle compared to the calf could be fit problems with the compression tights. As identified by the fit analysis, there were problems with the length of the tights leading to the fabric of the tights bunching up at the ankles and, thus, not applying sufficient levels of pressure. There was also a problem with the bonded hems at the ankles and at the wrists. Whilst they were very stretchable, they did not fully recover, which could result in decreased pressure application over time.

When comparing the in vivo pressure levels measured on the participants with the in vitro pressure levels measured on the mannequin, the results showed that there were significant differences at many PM locations despite using a soft series mannequin, which was claimed to resemble human tissue. The mean chest and narrow waist circumferences of the mannequins and WT participants were comparable with only the participants' hip girth being 3.6cm bigger than the mannequin's hip girth. Variations in limb circumferences were within the range of ±1cm with the exception of ankle girth. The ankle girth of the mannequins was 1.5cm larger than the mean ankle girth of the WT participants.

There were significant differences between the pressure levels measured on mannequins and the WT participants at five measurement locations with the pressure being significantly higher on the mannequin at all five locations. The PM locations with no significant differences in pressure values were B31, B71, B81 and B91. With the exception of B31 (calf), these PM locations were at the lower torso: 5cm below waistband on side (B71), 10cm below naval (B81) and the waistband (B91). Body tissue is generally soft in these areas, whilst there are no big protruding muscles or bony prominences. The composition of the body surface did likely not differ too much at these locations between the mannequins and the human bodies resulting in similar pressure levels. For the compression top, there were significant differences in pressure values at the waist (T41), neckline at CF (T71), biceps (T111) and wrist (T131) with the biggest difference in pressures at the wrist. The neckline at CF, biceps and wrist are all areas with bony prominences or bulging muscles. Pressures around the torso area did not differ significantly. The waist (T41) was the only location where pressure levels were significantly higher on the participants compared to the mannequins. There was a fabric strip at the waist of the mannequin (see Figure 8.15), which could have resulted in the pressure differences between the participants and mannequins.

Figure 8.15: Waist of AlvaForm soft series mannequin

As the findings show, the mannequins did not accurately resemble a human body. Whilst the mannequin featured a soft memory foam surface that could be comparable to human soft tissue, it did not feature any muscles or bony prominences. As has been shown by previous research (Sawada, 1993) using sponges and plastic plates to simulate body fat and bony prominences, variations in body composition affect compression levels. Overall, pressure levels were higher on the mannequins and were closer to gradual compression and therefore likely closer to the desired pressures on the human body. Many existing studies only measure compression levels in vitro. This is especially common in medical compression, where applied pressure of MCS is generally measured on wooden legs. The results of this study showed that body composition significantly influences pressure levels. Hence, only measuring pressures in vitro when designing SCGs can potentially lead to misleading pressure assumptions, as pressures applied by the garments to human bodies might vary significantly. Variations in body compositions across SCG users also have to be considered, as body composition, for instance at the waist, can vary widely within one size category, as was shown by this study.

Mean pressures applied by the compression top around the torso were fairly low. This could be associated to the sizing system, which was based only on the wearer's chest circumference. Participants with the largest difference between chest and waist circumference (>10cm) had low PMs at all three torso PM locations (T21, T31 and T41). The mean pressure level at the torso hem (T11) was slightly higher due to an elastic band with silicone coating that was used at the hem to keep the top in place. There were also problems with the applied pressures at the sleeves of the garments. The forearm (T121) and the wrist (T131) were the only PM locations with significant differences in pressure values across sizes (S-M, S-L). Whilst the grade increment of the sleeves from sizes M to L was slightly lower than from size S to M, mean arm circumferences at biceps, forearm and wrist between sizes S and M did not differ much, but there were larger variations in arm girths between sizes M and L. This observation is conflicting with the PMs, which did not differ significantly between sizes M and L as would be expected based on the variations in arm girths and grading.

The pressure analysis showed that there were not only high pressure variations between different PM locations across the body, but also between the 33 individuals at key measurement locations (e.g. calf (B31): 7-23mmHg for tights and waist (T41): 1.5-11mmHg for top). This means that consumers do not know how much pressure SCGs will apply to their body when purchasing SCGs. Researchers (Troynikov and Ashayeri, 2011; Brophy-Williams et al., 2015; Hill et al., 2015) have made the assumption that variations in pressures could be related to a wide range of limb circumferences within each size category. The WTs found that there was a wide range of limb circumferences within each size category. According to Laplace’s Law, a larger radius would result in lower pressure values under the influence of the same tension. Correlations between pressure levels and circumferences, could however, only be found at the gluteus maximus (B61) in size M and the biceps (T111) in size L. These correlations were positive, meaning increases in circumferences would lead to increases in pressure. This indicates that fabric tension increased more than the circumference as the fabric stretched over the larger body. However, it needs to be considered that the human body is not cylindrical in shape, especially not at the torso and Laplace’s Law is based on cylinders. In addition, it has been shown that not just fabric tension and limb circumferences, but also fatty tissue and bony prominences can affect pressure levels. As a result, finding correlations that could help predicting pressures is very complex.

The analysis of the pressure data from all four body postures showed that there were significant variations in pressure levels based on movement. The only exception was at the calf in Posture 2 (B32). This exception was not surprising, as calf muscles are not activated when lifting the leg to 90 degrees. It was obvious that in the tiptoe posture (Posture 3) all pressure values decreased. This was also the case for the pressure at the two calf locations (B23 and B33). However, pressure levels increased by more than 50% above the knee (B42), at mid-thigh (B52) and at the gluteus maximus (B62). These large variations in pressures were likely related to fabric tension, which was increased with the fabric being stretched across the body. The same observation was made for the shoulder blade (T54). As was highlighted in Appendix A, movements of the human body result in dramatic skin stretching, especially at the knee and elbow, where the skin is stretched up to 50% when the knee and elbow joint are bent.

There were also pressure increases at the biceps (T114) and forearm (T124), which could be related to variations in limb girth shapes due to muscle contractions, like the calf measurements. Whilst the percentage pressure changes of the top appear high at first glance, the actual variations in pressure values were moderate due to the low pressure values measured at these locations. The highest variation in pressure values occurred at the biceps where pressure increased by 2.7mmHg. The largest absolute change in mean pressure levels of the tights was 5.1mmHg, which is comparable to the results of existing research (MacRae et al., 2012) that found that there were variations of around 6mmHg when measuring pressure on the front mid-thigh and calf of twelve male participants during cycling.

Interestingly, quantified pressures were not necessarily related to the wearers' perception of compression levels. For instance, participants stating that compression was too tight did not necessarily have higher than average pressure levels applied to their bodies.

8.8 Chapter Conclusions

This chapter presented the results of WTs with women's Skins A400 compression sportswear. The body dimensions of the 33 female participants were analysed alongside the garment fit and applied pressures. The pressure analysis offered a more detailed insight into applied pressure levels and pressure distribution of SCGs than any existing research, as pressure was measured at 22 locations across whole-body SCGs. The only comparable studies measuring compression of whole-body SCGs measured pressures at a much more limited number of locations with MacRae and colleagues (2012) measuring compression at three locations and Sear and colleagues (2010) at eight locations. This study also had a substantially higher number of participants and was the first study to focus on the female body. It was, thus, able to give a much more comprehensive picture of the pressure application of commercial full-body SCGs across the whole body including compression in different body postures.

The sizing system applied was not the most suitable for the anthropometric data of the WT participants resulting in fit problems at the sleeves and problems with the length of the compression tights. These fit problems triggered problems with pressure levels and distribution of applied compression.

It was difficult to recruit participants that would fit into size L of the compression tights, as the size chart for the tights was very ‘generous’ compared to the size chart for the top. This meant that most participants wore a smaller size in the tights than the top, indicating problems with the size chart that was based on height and weight measurements. More studies with larger sample sizes within each size categories and a selection of different SCGs are needed to further examine the correlation between body dimensions and pressure distribution.

The study demonstrated that the pressure application of the commercial women’s SCGs under investigation was not well controlled and it is questionable if the pressure levels were sufficient and distributed adequately to have any physiological effects on the wearer to improve exercise performance or recovery.

Findings from the WT questionnaire highlighted the importance of wearer perception, which can have a positive or negative effect on the wearer depending on fit preferences and body cathexis.

9 FINDINGS FROM PHASE III: PRESSURE PREDICTION

9.1 Chapter Introduction

Virtual fit, the process of virtually ‘sewing’ two-dimensional (2D) garment patterns around body avatars (Porterfield and Lamar, 2016), is claimed to provide designers with meaningful fit and design assessments without the need to produce physical prototypes. However, cloth simulation is far less matured than the simulation of solid objects due to the anisotropic character of fabrics, which needs to be simulated in combination with the forces exerted by the body wearing the garment (Volino et al., 2005). The technical challenge for three-dimensional (3D) computer-aided design (CAD) software systems for virtual fit is, therefore, to realistically simulate the human body as well as soft cloth and its respective characteristics when worn on a human body (Goldstein, 2009).

As has been discussed in section 3.6.3.2, current commercial clothing-specific 3D CAD systems have substantial shortcomings in achieving this challenge. Researchers have highlighted limitations in the realistic representation of technical garment aspects, such as fabric (Wu et al., 2011; Power, 2013) and seam (Lee and Park, 2016) properties, which can affect the way simulated garments fit body avatars.

Most clothing-specific 3D CAD programmes feature built-in heat maps, which provide a visual and numerical assessment of pressure, tension or distance values at the body-garment-interface. Fit assessments based solely on the visual assessment of the colour coding of the heat maps have been found to be not sufficient as a decision making tool in design and product development (Kim, 2009; Lim, 2009; Power et al., 2011; Kim and LaBat, 2013; Power, 2013). Only few researchers (Allsop, 2012; Sayem, 2017b; Sayem and Bednall, 2017) have attempted to use built-in pressure maps for the numerical evaluation of garments. However, there are no studies assessing the accuracy of the numerical values provided by pressure maps. If these pressure map tools realistically represented pressures applied by a garment to the underlying body, they would be a simple means to control pressure levels and distribution of the finished sports compression garment (SCG) throughout the design phase. It could also facilitate the production of custom SCGs for athletes.

This chapter presents the findings from Phase III of this research. Phase III set out to evaluate the use of virtual fit technology to predict pressures applied by SCGs to the underlying body. Under consideration of previously reported limitations of clothing-specific 3D CAD programmes, the study focused on creating a better understanding of how the various simulation settings affect the visual simulation and heat maps in order to define a process that could overcome these deficiencies and result in realistic fit and virtual pressure simulations. This was a novel approach, as existing research has only focused on a small number of simulation parameters (mainly fabric properties), but has mostly ignored the effects of other simulation settings. The study further repeated the wearer trials (WTs) from Phase II – Study 3 in a virtual way and compared absolute in vivo and virtual pressure levels. No published research has previously compared absolute values of in vivo and virtual pressures of commercial 3D CAD programmes.

The chapter gives an overview of the data import, the virtual fit process in Optitex Pattern Design Software (PDS) 11 (EFI Optitex, Israel) and the encountered problems with the virtual fit of SCGs. It then presents the findings from the analyses of the effects of simulation settings on simulation quality and virtual pressure followed by the findings of the virtual WTs. Finally, the chapter evaluates the feasibility of using Optitex as a pressure prediction tool for the design of SCGs. The chapter fulfils Aim 5 of the research project.

All images used in this chapter are screenshots taken by the researcher throughout this study. The different Optitex-specific 3D settings and terminologies were described in section 4.4.4.

9.2 Objectives of Evaluation of 3D CAD for Pressure Prediction

The objectives of Phase III were defined as follows:

1. To better understand the effects of different simulation settings on the quality of garment fit simulation and virtual pressure levels.
2. To compare virtual pressure values to in vivo pressure values.

3. To assess the feasibility of applying 3D CAD virtual fit as a tool for pressure prediction in the technical design process of SCGs.

9.3 Data Import

The first stage of the virtual fit process was the import of the WT participants' body avatars from Phase II - Study 3 (Chapter 8), the re-engineered Skins A400 garment patterns from Phase II - Study 2 (Chapter 7) and the related fabric data.

9.3.1.1 Body Scan Data

Body scanning has its limitations related to the amount of details that can be captured by the scanner sensors, thus body scan avatars created by the scanning software from the raw scan data (OBJ-files) can result in uneven body surfaces. The main problem with the Size Stream scanner used in this study was data occlusion in the underarm area. 3D body scanners are designed to scan bodies in standing position with arms abducted to form a 20-degree-angle between the upper arms and the sides of the torso (refer Figure 4.11). As a result, underarm areas cannot be fully scanned by the sensors as they would if the body was scanned in a T-pose. Thus, body avatars generated from raw scan data are frequently not directly usable for virtual fit.

The cleaned refined body meshes (RBMs) from the body scans in Phase II were checked to ensure that they are suitable for virtual fit. It was found that all body avatars had no distinct axillae. There was a 'webbing' in the underarm area. The same problem often exists in the crotch area of body scans, however, with the particular scanner utilised in this study (Size Stream SS14), problems with the crotch area were only present for participants with large thigh volumes. Some of the body scan files also had 'bumps' at various locations of the contour of the body (e.g. Figure 9.1) and the body surface was generally not particularly smooth. Since avatars in 3D CAD are solid objects created by all points in the point cloud, it was impossible to fit the SCGs to the original RBMs. The 'webbing' and 'bumps' inhibited the virtual fitting of the garment as shown in Appendix LL.

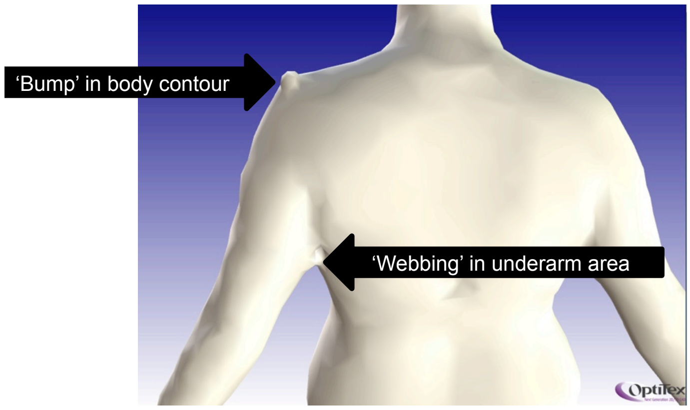
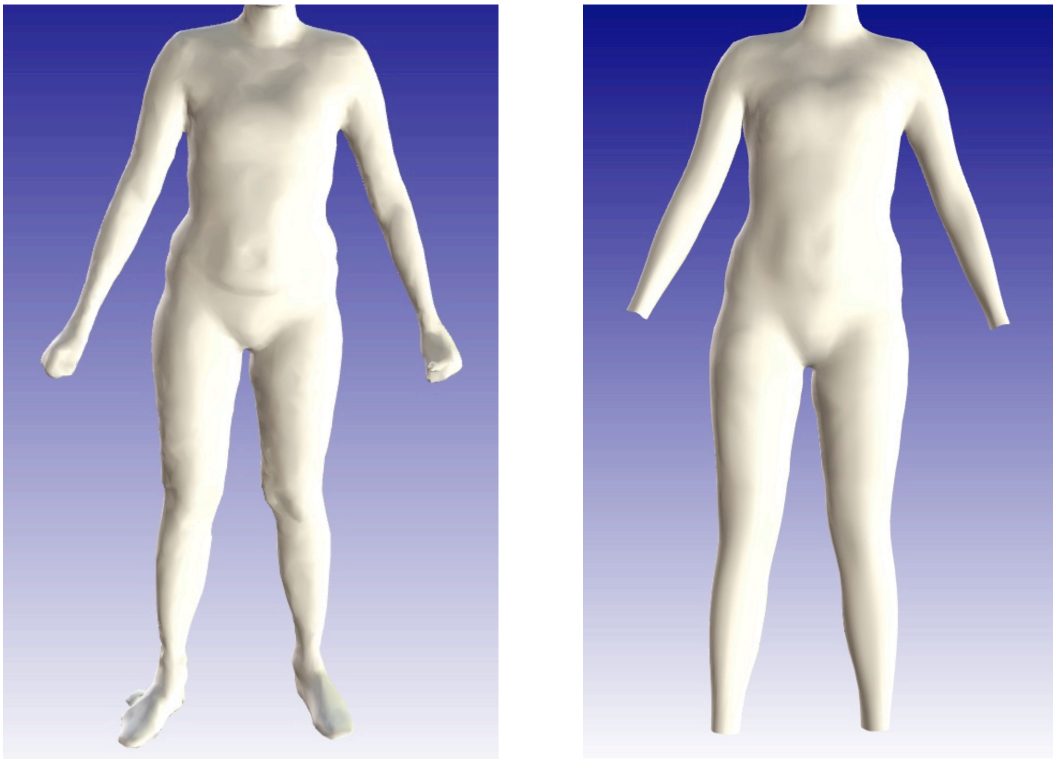


Figure 9.1: 'Bump' on left shoulder and 'webbing' in armpit of scanned body

To make the body avatars usable for virtual fit, the avatars had to be retopologised using 3D modelling software to smooth the surface of the avatars and remove the aforementioned 'webbing' and 'bumps'. OBJ-files are 3D geometry files, which can be opened in most 3D graphics applications. It would have been possible to move each individual point and manually reshape the avatar, however, this process would have been very time-consuming and subjective, whilst demanding advanced knowledge of 3D modelling software. This study, therefore, utilised the expertise of a 3D animation computer expert who developed a novel remodelling process to retopologise the surface of 15 randomly-selected WT avatars, resulting in smooth avatars that could be used for the virtual fit process. An example of an original and remodelled file is shown in Figure 9.2. Appendix MM shows different stages of the remodelling process and the point clouds forming the RBM and the remodelled avatar, with the latter being arranged in straight lines.



a) b)

Figure 9.2: Example of an original scan file (RBM) (a) and a remodelled body avatar (b). The remodelled avatar has a smoother surface and 'webbing' in the underarm area is eliminated. Hands and feet were removed as they were not required for this research.

The accuracy of scanned head, hands and feet is generally very limited with most 3D body scanners. This was also the case with the Size Stream body scanner. Consequently, the head, hands and feet were excluded during the remodelling process, as they were not required for this study.

In order to ensure that the remodelled body avatars still represented the body measurements of the WT participants, the circumference measurements of the RBMs and the remodelled avatars were compared. The researcher tried to open the remodelled OBJ-files in Size Stream Studio to extract body measurements that could be used to verify the dimensions of the remodelled file. However, as all landmarks were lost during the remodel process, no measurements could be extracted. Instead, the Optitex circumference measurement tool was used to extract and compare circumference measurements of the original RBMs and the remodelled OBJ-files. The circumference tool is a horizontal disk that can be placed anywhere on the body avatar by moving it up or down the body. As it was difficult to identify certain positions on the body avatars accurately, the measurements used for the control of the remodelled body avatars were reduced to the chest, small of waist, seat, right thigh and right knee circumferences. Difficulties presented themselves with obtaining accurate chest circumference measurements from a number of the original RBMs because of the 'webbing' in the underarm area that extended down to the bust level. As a consequence, the final control measurements used were the small of waist, seat, right thigh and right knee circumferences as shown in Figure 9.3.

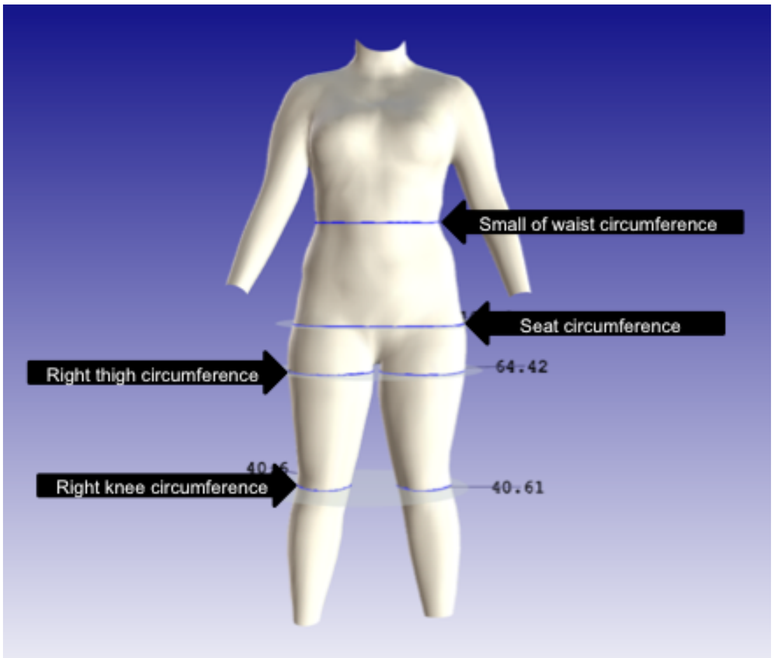


Figure 9.3: Circumference measurements used to analyse remodelled body avatars

The mean discrepancies in circumference measurements at the narrow waist, and seat were miniscule (±0.5%). Mean variations at the right thigh and right knee were also well within acceptable tolerance (±2%). Appendix Table MM-1 presents the individual discrepancies for each body avatar. Variations in the thigh and knee measurements were likely slightly higher due to the difficulty of placing the circumference measurement disk to the exact measurement locations at the thigh and knee. The identification of the knee was especially difficult on the remodelled files, as the definition of the knee was not as distinct. It was concluded that the remodelled body avatars were representative of the WT participants' bodies.

To further test the validity of the remodelled body avatars, a mannequin was scanned and the resultant RBM was smoothed using the developed remodelling process. Circumference measurements extracted using the Optitex circumference tool were compared to manual measurements of the mannequin. The mean discrepancy between the Optitex and manual measurements was -1.4% (see Appendix Table MM-2), leading to the conclusion that the remodelling process did not affect dimensions of the body avatar. Hence, the remodelled OBJ-files were used in this study.

9.3.1.2 Garment Data

The re-engineered, graded garment patterns of the women's Skins A400 SCGs were imported in DXF-format and saved in the Optitex pattern file format (.pds).

9.3.1.3 Fabric Data

As the main fabric (Fabric A) used in the SCGs was sent to Optitex for testing, the researcher obtained an Optitex fabric file in fdf-format containing the relevant fabric properties (refer section 4.4.4.2). Once the file was added to the fabric file directory, it could be selected via the fabric list in the 3D properties window in Optitex.

Only Fabric A was sent to be tested by Optitex, as the fabric panels of the other fabrics were too small to test. As a result, some variations may have existed in the fabric properties used in the virtual fit process. It was attempted to convert the results obtained from the FAST (Fabric Assurance by Simple Testing) system in Phase II of this research into the units required by Optitex. However, the results varied substantially from the fabric parameters supplied by the Optitex Fabric Testing Unit (FTU) as shown in Table 9.1. It was further attempted to convert the results of the Fryma extension test to the stretch unit used in Optitex (g/cm). Again, the results differed from the Optitex values (Table 9.1). Potentially, the disparity in stretch values occurred because stretch is generally non-linear and the stretch values measured with the Fryma extensiometer were stretch values under 3kg of weight, so a linear conversion of the absolute extension (mm) per 3000g into grf/cm is likely not a realistic representation of the anisotropic stretch behaviour of Fabric A.

The fact that the results did not correlate well highlights concerns with the Optitex FTU, since objective fabric testing could not reproduce the figures. Optitex needs to be more transparent about how these results were obtained rather than following a 'black box' approach in an attempt to make their customers dependent on their fabric testing services.

Table 9.1: Properties of Fabric A based on Optitex FTU results and the conversion of data from the fabric analysis in Phase II

		Optitex test results	Converted FAST and Fryma results
Bending (dyn•cm)	X	2.46	28.18[a]
	Y	10.91	28.18[a]
Thickness (cm)		0.05	0.07
Weight (gsm)		228.67	206.4
Shear (grf/cm)		84.4	-
Friction		0.34	-
Stretch (grf/cm)	X	190.29	201.61
	Y	285.61	370.83

a: Based on 1 μN•m = 10 dyn•cm

9.4 Virtual Fit in Optitex

9.4.1 Virtual Fit Workflow in Optitex

Each of the 15 remodelled body avatars of the WT participants had to be virtually fitted with the SCGs under investigation. The virtual fit workflow in Optitex is summarised in Figure 9.4. Before the SCGs could be simulated to the remodelled body avatars of the WT participants, the patterns had to be prepared for 3D. All pattern pieces had to be organised to match the direction on the body when worn, regardless of the direction of the grain line. Once all 3D and fabric properties were set, pattern panels were placed around the body avatar with a distance to the body so that the garment and body did not collide. The virtual stitching involved selecting line segments of different pattern pieces that were to be joined and defining stitch properties. The 3D window was used to check that stitches had been allocated to all garment panels (Figure 9.5) and that seams had the right sewing direction (Figure 9.6 and Figure 9.7). Following this, the simulation was started.

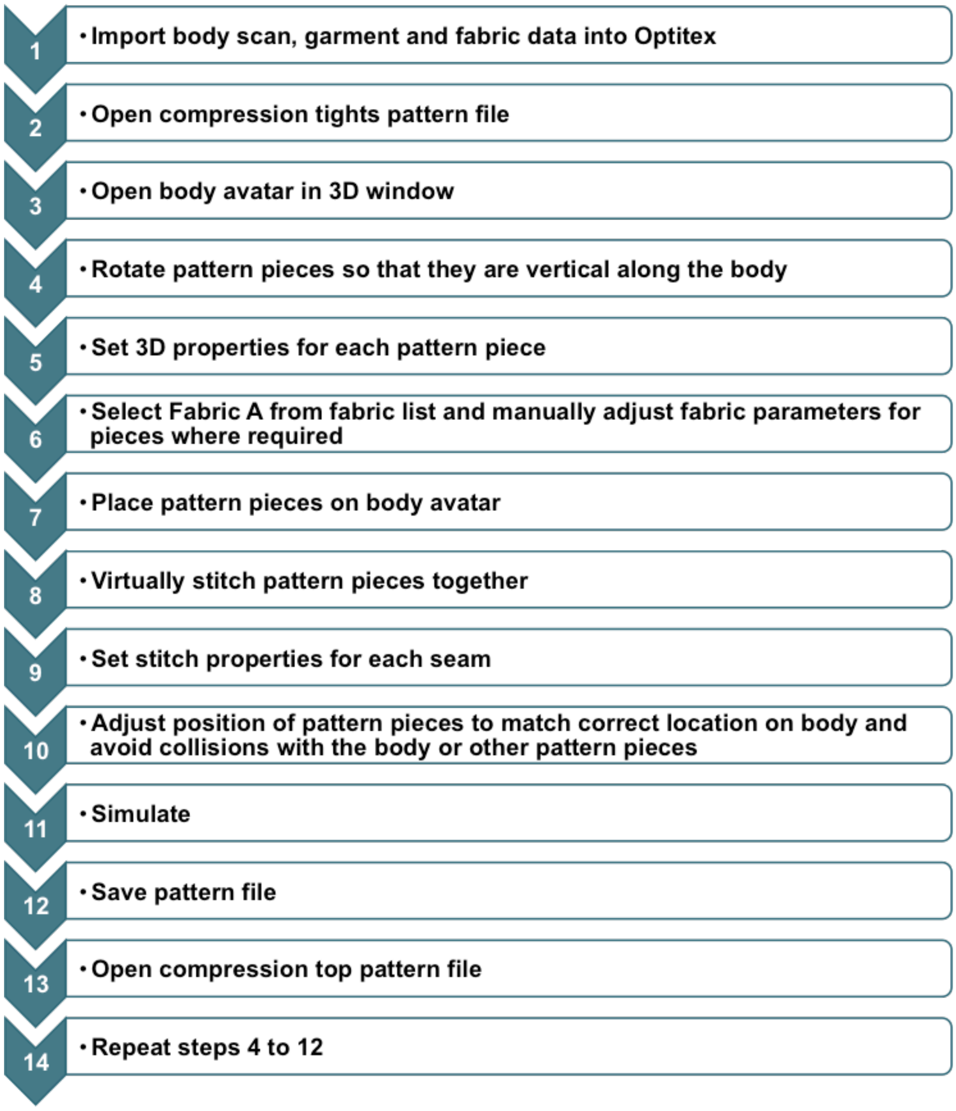
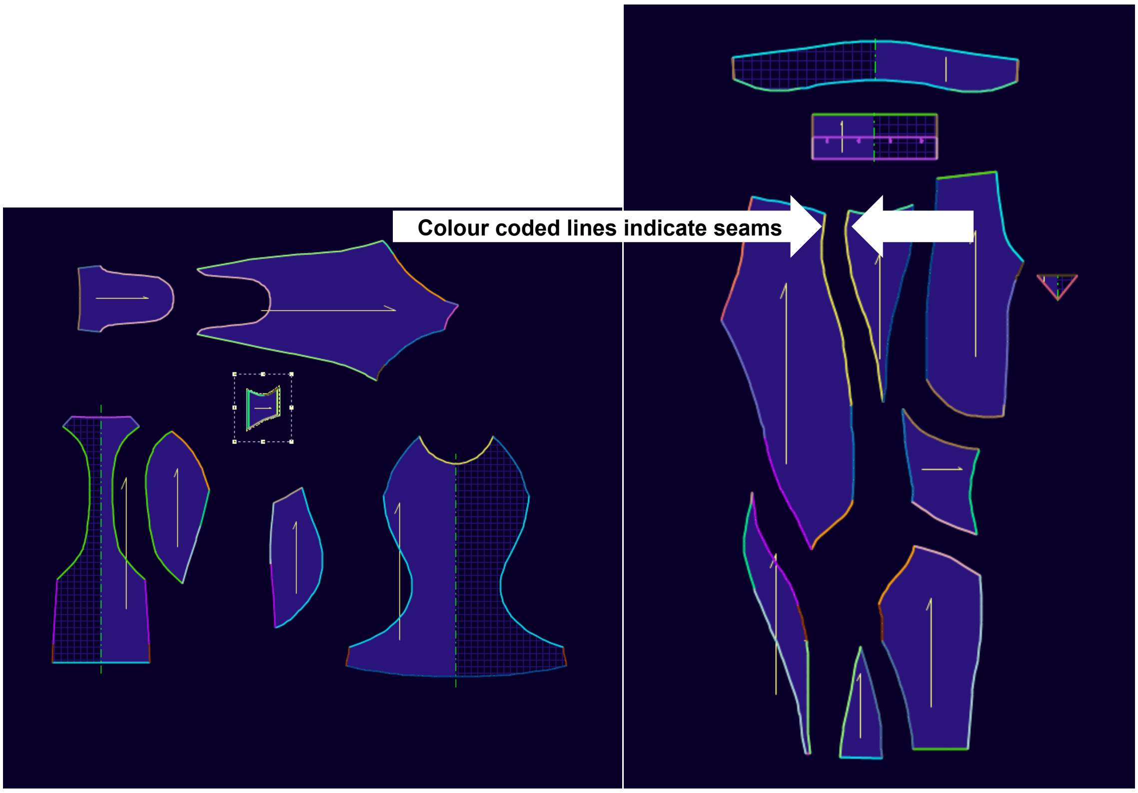
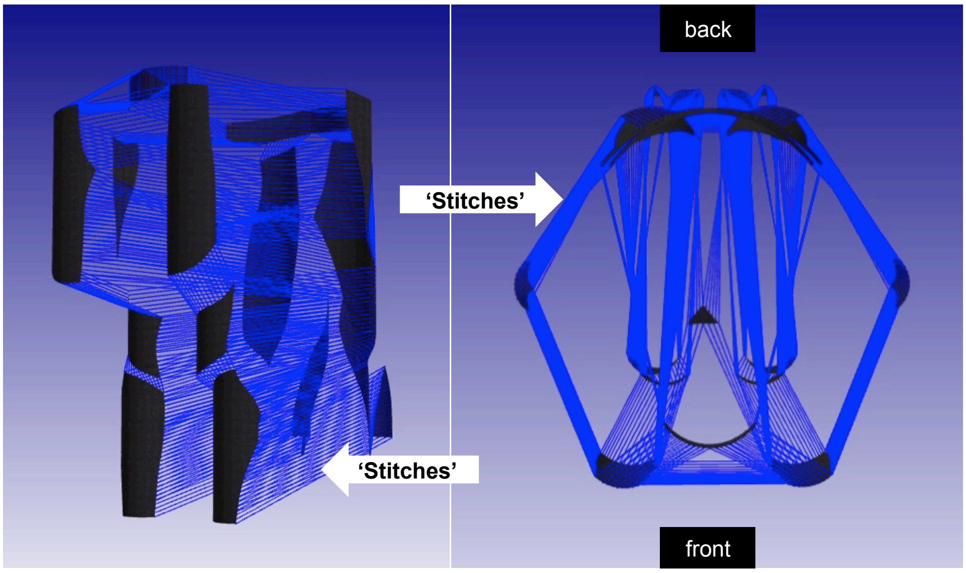


Figure 9.4: Virtual fit workflow in Optitex for this study



a) b)

Figure 9.5: Stitches allocated to pattern pieces of the compression top (a) and tights (b). Matching coloured lines indicate seam lines to be joined in virtual 'sewing' process.



a) b)

Figure 9.6: View of allocated stitches in 3D with avatar hidden to check stitch allocation and directions prior to simulating the garment on the body avatar: a) side view of tights; b) top view of tights

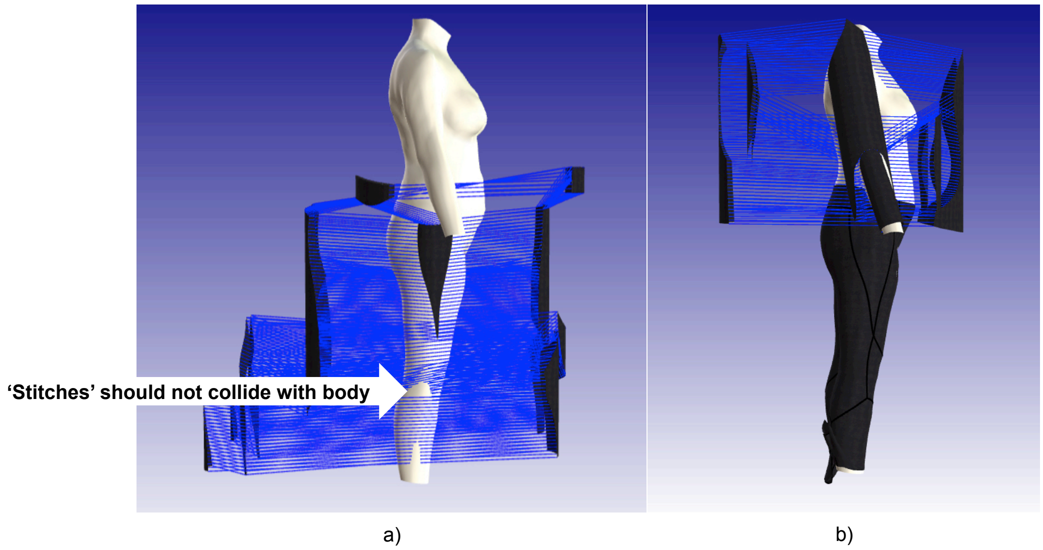


Figure 9.7: Placement of prepared garment pattern on body avatar in 3D: a) compression tights; b) compression top with tights already virtually fitted.

9.4.2 Normal Collision Pressure Map in Optitex

The built-in Normal Collision Pressure (NCP) map in Optitex was used to virtually measure the pressure levels applied by the SCGs to the body avatars. As per default settings, NCP maps present the distribution of pressure from minimum (blue) to maximum (red) with green and yellow colour nuances in-between. Figure 9.8 shows the simulation of the re-engineered SCGs on one of the WT participants' remodelled body avatar. Pressure levels at the seams were unrealistically high, ranging far beyond compression capabilities of garments (approx. 90-450mmHg) and much higher than at the rest of the body. As a consequence, the NCP map did not show detailed variations between pressures across the body, i.e. the heat map looked mainly blue and green. It was not clear why pressure levels at the seams were this high and changes in stitch settings did not eradicate the problem. It was, however, possible to manually adjust minimum and maximum values to change the pressure range displayed by the NCP map. Pressure levels applied by SCGs generally range between approx. 5 and 30mmHg, only rarely reaching levels above 30mmHg (refer section 2.6.2.1). To give the reader a better visual representation of the pressure distribution across the body, the NCP maps were set to a maximum of 30, 20 and 10mmHg in Appendix NN.

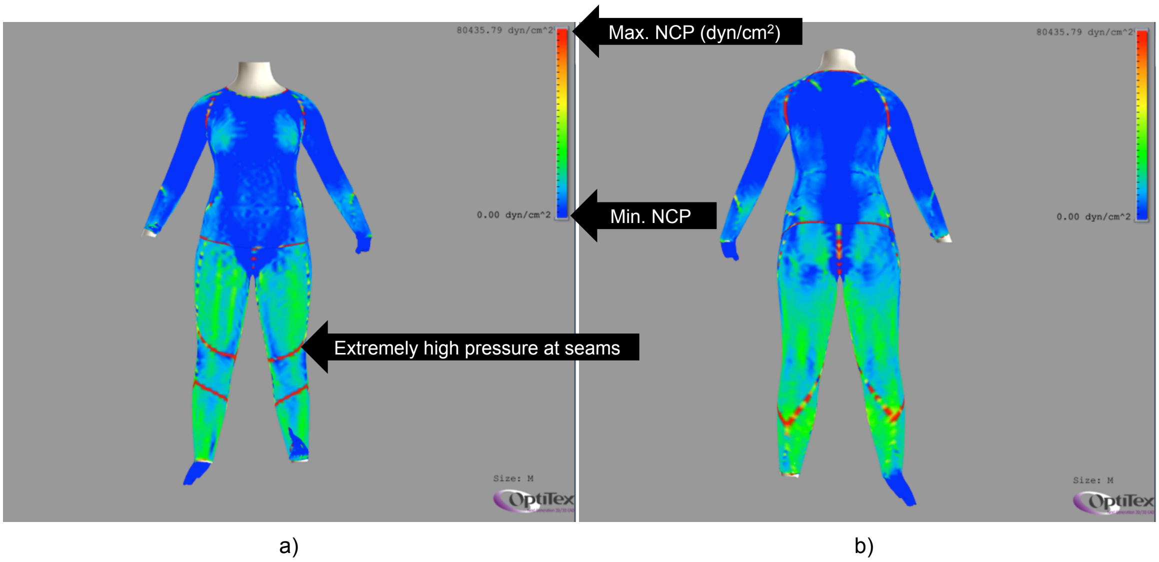


Figure 9.8: NCP map of compression tights and top on remodelled body avatar in Optitex: (a) front view; (b) back view. Colours representing NCP from lowest to highest pressure: dark blue – green – yellow – red.

9.5 Problems with Virtual Fit of Sports Compression Garments

The actual simulation of the garment (virtual stitching and wrapping of the pattern pieces around the body avatar) only took a few seconds, however, achieving a successful simulation result was not a straightforward process. It was important to avoid any collisions of the garment and the body. As the SCGs were smaller than the participants' bodies, collisions of garment panels or stitches and the avatar were in some cases unavoidable and the simulation frequently resulted in failure or in seam gaps, particularly in the underarm area due to the raglan sleeve style (e.g. Figure 9.9). The sleeve simulation could be slightly improved by ensuring that the seams wrapped around the arms, even if that meant that the fabric clashed with the arms.

Figure 9.9: Problems with seam gaps in underarm areas: a) front view; b) back view

It was also particularly difficult to fit the compression tights at the lower legs (e.g. Figure 9.10), which was likely caused by unavoidable collisions of stitches and the body avatar. With one garment panel wrapping around the shin joining at the calf and two smaller panels joining it at the calf, it was difficult to place the panels around the lower leg without any collisions between the ‘seam threads’ and the body.

a) b)

Figure 9.10: Problems with simulation of tights at lower leg: a) problems at ankles; b) problem at right leg only

There were also problems with fabric gaps in some of the simulations (e.g. Figure 9.11). These fabric gaps were not related to the joining process, but were located centrally on garment panels. It appeared to be a fault in the software, as despite many re-simulations with different settings fabric gaps could not be avoided. The software was unable to simulate the high stretch levels of the fabrics caused by the negative ease of the SCGs.

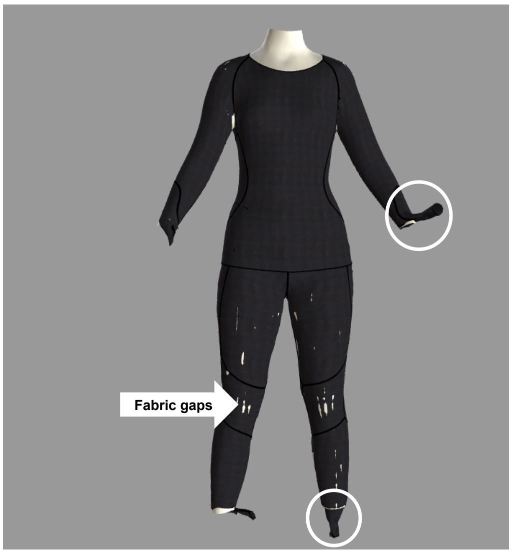


Figure 9.11: Problems with fabric gaps and excess fabrics at wrists and ankles (circled)

Most fabric gaps were located at the legs of the tights. Garment stretch at the legs was much higher than garment stretch at the arms (refer section 8.4.1.5). Therefore, there could be a relationship between fabric gaps in the simulation and garment stretch. The garment stretch percentage values at locations mid-thigh (B51), knee (B41) and calf (B31) obtained in Phase II of this research were compared to the average garment stretch values for the relevant size at these locations (refer Appendix OO). Body avatars with fabric gaps were grouped and their garment stretch percentage values compared to the body avatars without fabric gaps in the simulation. However, no clear relationships could be identified between fabric gaps and garment stretch percentage.

As can be seen in Figure 9.11, there were also problems with excess fabric at wrists and ankles. As reported in the previous chapter, sleeves and legs of the SCGs were too long for many participants creating folds and wrinkles at the ankles and wrists when worn during the WTs. However, the software was unable to simulate this behaviour. In some cases this caused problems as the excess fabric protruded unnaturally.

The success of the simulation strongly depended on the positioning of the garment panels around the body avatar. Moving garment panels only slightly to the left/right or up/down had big effects on the quality of the simulation. For instance, a simulation attempt could fail, but when moving a single panel only the slightest amount, it could succeed. In a different case, there were problems with the simulation of the lower leg at the right leg. The calf panel was slightly moved outwards and the garment was re-simulated. The result was an improved simulation of the right leg, but a large hole at the knee and calf of the left leg appeared, even though no changes had been made to the left leg. A slight movement of a garment panel could mean the difference between a successful and an unsuccessful simulation, regardless of 3D simulation properties. With no apparent logic behind it, it made the process very cumbersome.

It took many attempts in panel placement and settings to eventually get a successful simulation of each of the 15 body avatars used in this study. The main problem with obtaining the best visual simulation results was that the same settings had to be used across all 15 body avatars in order to be able to compare pressure maps. However, even the final simulations were not perfect. The double layer fabric on the side of the tights and at the waistband were kept as single layers due to simulation problems and the elastic webbing at the front of the waistband could not be simulated realistically. There were further still seam gaps in the underarm area and fabric gaps at the lower legs for some WT participants. The described problems represent major barriers in the application of 3D CAD software and the usefulness of virtual fit for the technical evaluation of garments. Many of the problems encountered seemed to be caused by glitches in technology.

9.6 Analysis of Simulation Properties

As there were no existing research or guidelines on the various simulation properties in Optitex, the effects of different 3D simulation settings on the simulation quality and the NCP map were assessed. The values were further manipulated in the attempt to create a better understanding of their relation to realistic properties, which could lead to the development of a process that would result in realistic garment fit and pressure outputs.

9.6.1 Effects of Resolution Settings on Simulation and Pressure Map

An Optitex consultant advised that changes to resolution settings could reduce the appearance of fabric gaps. Additionally, virtual pressure values of default resolution settings and high resolution settings were compared on one body avatar to explore the effects of resolution settings on NCP levels.

9.6.1.1 Effects of Resolution Settings on Simulation Quality

Various different resolution settings were explored in an attempt to improve simulation quality. Changing resolution settings had different effects on the simulation of the same garments on different body avatars. The resolution settings resulting in reduced fabric gaps for the garment simulations on most body avatars (e.g. Figure 9.12) are presented in Table 9.2. Whilst there were positive visual effects with higher resolution settings in some cases, the simulation process also slowed down extensively and resulted in simulation problems at the lower leg in three cases (e.g. Figure 9.13). The higher resolution settings resulted in simulation failure for six of the 15 body avatars used for this study.

The fact that changes in resolution resulted in simulation failure without changing any other 3D settings led to the assumption that resolution is linked to other simulation settings. Overall, simulations based on higher resolution settings with otherwise unchanged simulation settings were less satisfactory than simulations based on default resolution settings.

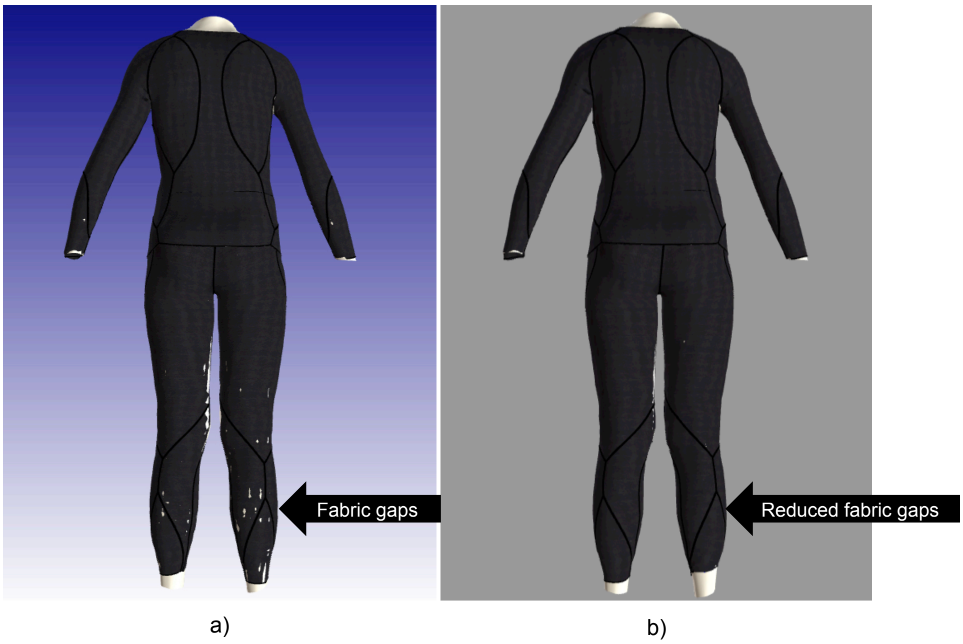


Figure 9.12: Fabric gaps in simulation (a) improved with higher resolution settings (b) for some avatars

Table 9.2: Selected high resolution settings

	Tights	High Resolution (cm)
Top	Bodice	1
	Side	0.8
	Underarm	0.8
	Back	1
	Shoulder	0.8
	Sleeve	0.8
	Sleeve insert	0.8
Tights	Waistband back	0.8
	Waistband front	0.8
	Thigh front	0.8
	Thigh back	0.8
	Thigh side	0.8
	Knee	0.8
	Shin	0.8
	Calf inner	0.6
	Calf triangle	0.6
	Crotch triangle	0.6

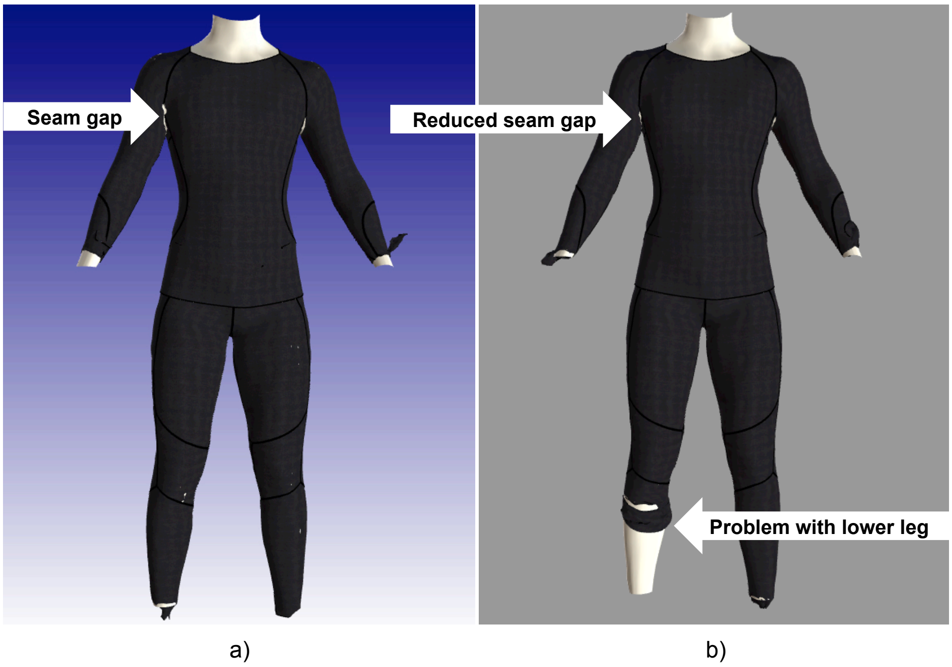


Figure 9.13: Simulation of lower leg with default resolution settings (a) and higher resolution settings (b)

9.6.1.2 Effects of Resolution Settings on Virtual Pressure

Pressure readings from simulated compression tights using default resolution settings and the same garment using the selected high-resolution settings are presented in Table 9.3.

Table 9.3: Pressure measurement readings from NCP maps

Measurement point	NCP (mmHg)	
	Default resolution	High resolution
B31	23.1	10.1
B41	18.7	22.2
B61	52.1	17.5

It is evident that pressure levels were largely affected by resolution settings, however variations in pressure values across default and high-resolution settings were not constant across the body. Increasing resolution settings of the compression tights resulted in notably lower virtual pressure values at the calf (B31) and gluteus maximus (B61), whilst slightly increasing pressures at the knee (B41).

To illustrate the pressure distribution across the body of the default and high-resolution settings, the NCP map was set with 30mmHg as maximum pressure in Figure 9.14. There were vertical lines in the high-resolution NCP map in contrast to the default resolution map. Depending on the exact pressure measurement (PM) location, pressure values could vary widely as is apparent by dark blue lines adjacent to red lines on the left thigh. This could be the reason for the high variations in pressure values.

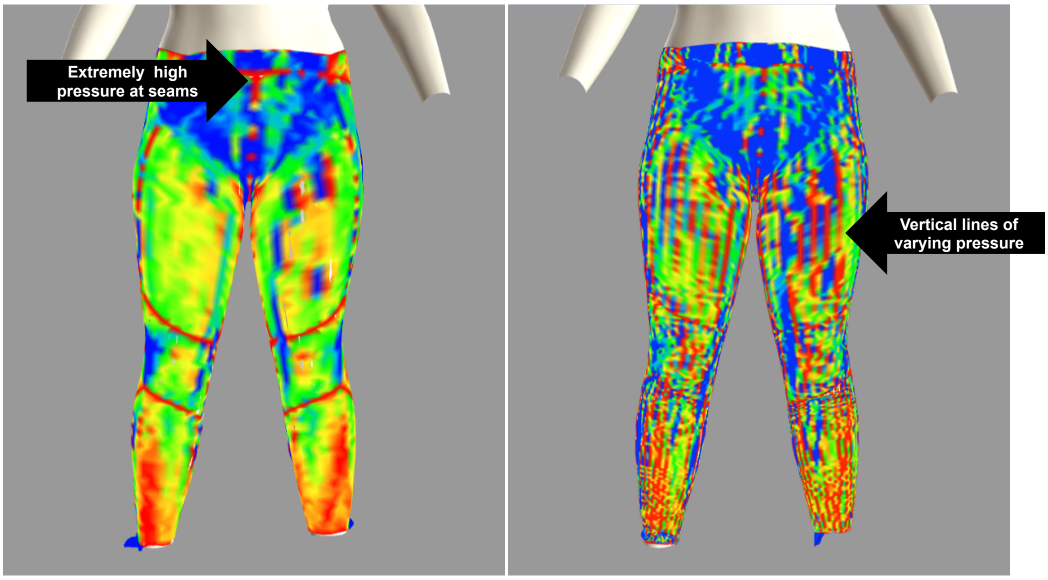


Figure 9.14: Maximum NCP set as 30mmHg: a) default resolution settings; b) high resolution settings. Colours representing NCP from lowest to highest pressure: dark blue – green – yellow – red.

The analysis of the effects of resolution settings showed that changes in resolution resulted in somewhat random changes in pressure values. Optitex have not explained how resolution settings are linked to garment or simulation properties.

As it was critical to use the same resolution settings for all body avatars to ensure comparability and to avoid variations in pressure readings, it was decided that the most suitable resolution settings were the default settings of 1cm for all pattern pieces despite small fabric gaps.

9.6.2 Effects of Global Simulation Parameters on Simulation and Pressure Map

The different global simulation parameters were changed one by one and effects on simulation quality and the NCP map were assessed.

9.6.2.1 Effects of Global Simulation Parameters on Simulation Quality

Changes in the Optitex global simulation parameters (time step, iterations, stitch constant and stitch damping) resulted in variations of the appearance of the simulation, such as gaps in the underarm area or at seams as listed in Table 9.4. Seam gaps were largely affected by stitch constant and stitch damping settings, however no clear relationship between global simulation settings and the appearance of underarm and seam gaps could be identified.

The stitch constant values resulting in the best visual simulation were different for the compression tights and top. It is not clear how exactly the stitch constant is related to other 3D simulation settings, but since the main difference between the compression tights and the top was the garment stretch percentage and the curvature of the underlying body, there could be a link between these factors. This requires further investigation.

Table 9.4: Visual simulation problems based on different global simulation settings

Global simulation settings				Simulation problems (visually)
Time step	Iterations	Stitch constant	Stitch damping	
0.02	10	250	0.15	Gap at UA, fold at back
0.01	10	250	0.15	Small gap at UA
0.01	20	250	0.15	Gap at UA
0.01	30	250	0.15	Gap at UA
0.02	10	100	0.15	Small gap at UA, fold at back
0.02	10	150	0.15	Gap at UA, fold at back
0.02	10	200	0.15	Small gap at UA, folds at back
0.02	10	300	0.15	Gap at UA, fold at back
0.02	10	350	0.15	Small gap at UA, fold at back
0.02	10	400	0.15	Gap at UA, fold at back
0.02	10	450	0.15	Small gap at UA, fold at back
0.02	10	500	0.15	Small gap at UA, folds at back
0.02	10	250	0.05	Gaps at UA, folds at back
0.02	10	250	0.25	Slightly twisted
0.02	10	250	0.5	Gaps at seams on neck
0.01	10	100	0.25	Gaps at seams on neck and hem
0.01	10	175	0.25	Gaps at seams on neck and hem
0.01	10	250	0.25	Slight gaps at UA
0.01	10	250	0.05	Gaps at UA, folds at back
0.01	10	250	0.2	Slight gap at UA

UA = underarm

9.6.2.2 Effects of Global Simulation Parameters on Virtual Pressure

Pressure levels in the NCP map were also affected by alterations in global simulation settings. Increases in iterations per frame resulted in large increases in maximum pressure values (refer Table 9.5), whilst the effects of changes to stitch damping and stitch constant on NCP were moderate and not linear (refer Table 9.6 and Table 9.7, respectively).

When examining the virtual pressure values, it was evident that the pressure values were considerably higher than the empirical pressures measured. This is likely related to the use of body avatar, as in this preliminary examination of the effects of global simulation settings a built-in parametric model was used.

It is important to note that the stitch constant value used here in the context of global simulation parameters is different to the stitch constant value defining sewing stitches, even though Optitex uses the same nomenclature. The stitch constant value here refers to the springs of the stitch during the simulation process, not the extensibility of the seam.

Overall, variations in global simulation properties had somewhat arbitrary effects on the visual simulation and pressure values.

Table 9.5: Maximum NCP values for different iterations per frame settings

Iterations per frame	Max. NCP (mmHg)
10 (default)	67.13
20	119.09
30	143.96

Table 9.6: Maximum NCP values for different stitch damping settings

Stitch damping	Max. NCP (mmHg)
0.05	73.61
0.15 (default)	63.76
0.25	70.75

Table 9.7: Maximum NCP values for different stitch constant settings

Stitch constant	Max. NCP (mmHg)
100	70.98
150	62.96
200	63.86
250 (default)	63.76
300	67.81
350	78.01
400	77.73
450	68.57
500	68.08

9.6.3 Effects of Fabric Parameters on Virtual Pressure

The Optitex fabric parameters bending, stretch, shear, friction, thickness and weight were adjusted one at a time and the NCP measurements recorded at locations T11 (hem at centre front) and T51 (shoulder blade). The fabric parameter adjustments frequently resulted in simulation failure as is evident by the gaps in the charts.

NCP values at T11 were overall higher than pressure levels at T51 with only very small levels of pressure at T51. The biggest variation in pressure patterns between the two PM locations T11 and T51 was observed with changes in bending properties (Figure 9.15). Pressure values recorded at location T51 were relatively constant under the different bending conditions in contrast to pressure values at T11. It is unclear why there is such a big difference between the effects on the two PM locations as there are no big variations in body curvature at these locations.

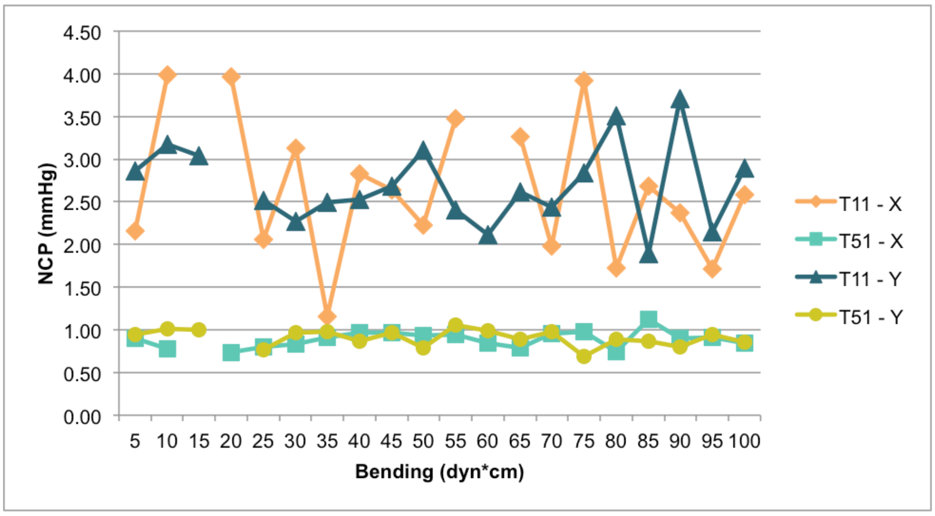


Figure 9.15: NCP at T11 and T51 for different fabric bending properties in X- and Y-directions

Changes in stretch parameters resulted in different pressure effects for X- and Y-directions at T11, whilst the effects at the shoulder blade were similar for both stretch directions (Figure 9.16). The compression top is stretched more around the circumference of the body at the hem (i.e. in X-direction) when worn. This could be a reason for an increase in pressure in X-direction.

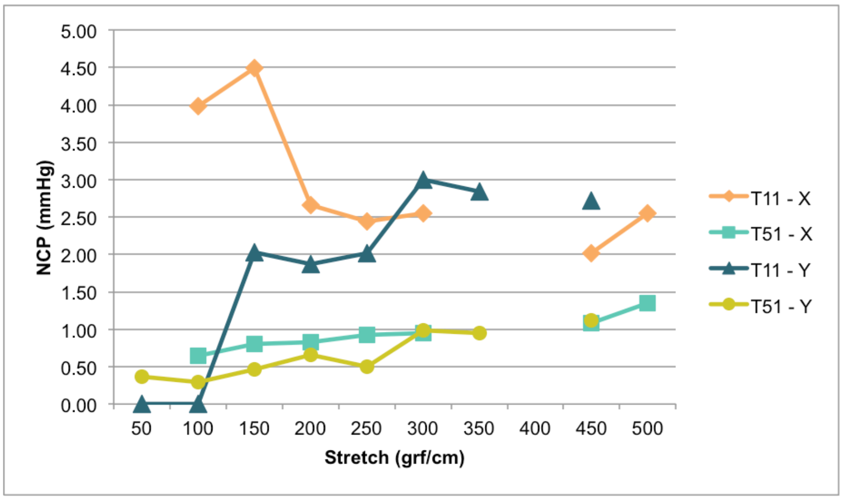


Figure 9.16: NCP at T11 and T51 for different fabric stretch properties in X- and Y-directions

Changes in fabric shear (Figure 9.17) and friction (Figure 9.18) resulted in pressure variations below 1.5mmHg, whilst fabric thickness appeared to have the smallest effect on pressure values with pressure levels being almost constant (Figure 9.19). Changes in weight settings, however, largely affected the simulation and resulted in failed simulations in most cases (Figure 9.20).

There was no clear pattern in how varying fabric parameters affected PMs, however it is clear that controlling fabric parameters is essential as changes in all fabric parameters bar thickness led to variations in pressure values. In order to achieve this, 3D CAD suppliers need to be more transparent about how their fabric parameters relate to physical fabric properties.

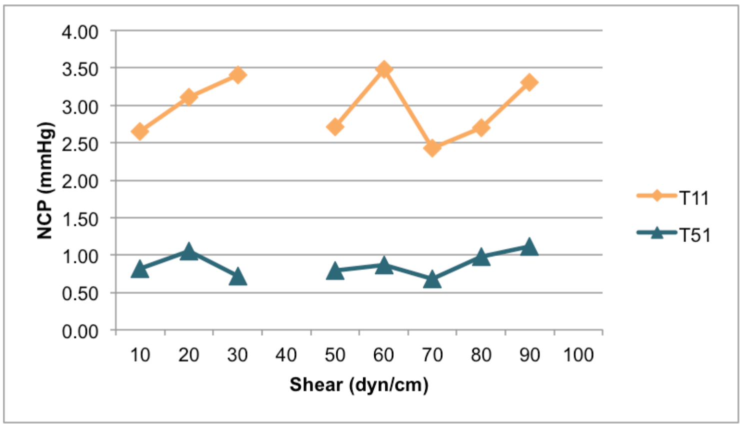


Figure 9.17: NCP at T11 and T51 for different fabric shear properties

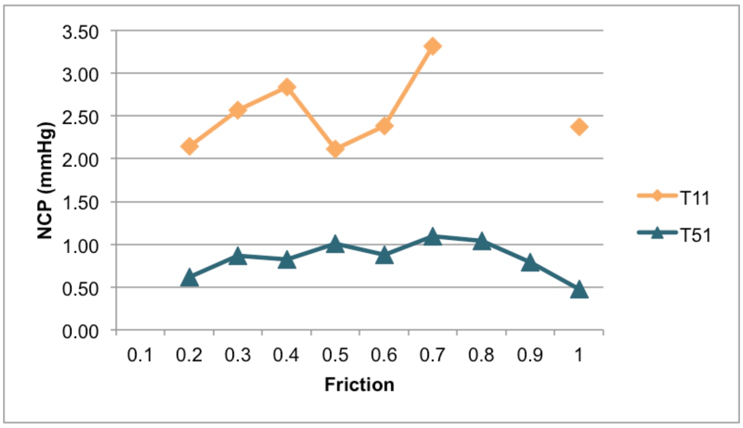


Figure 9.18: NCP at T11 and T51 for different fabric friction properties

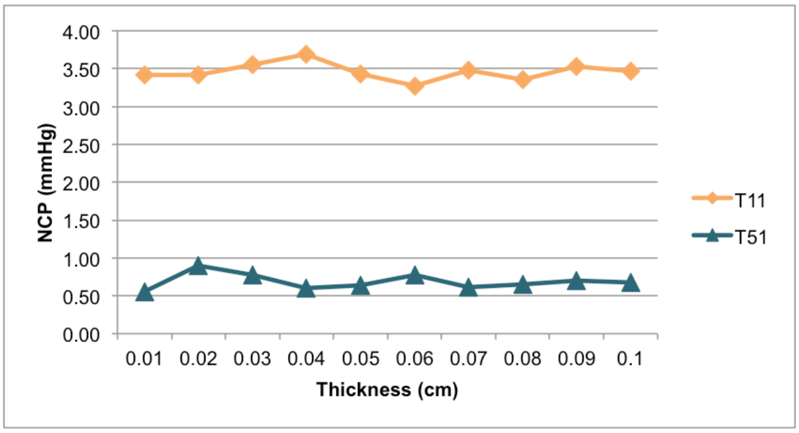


Figure 9.19: NCP at T11 and T51 for different fabric thickness properties

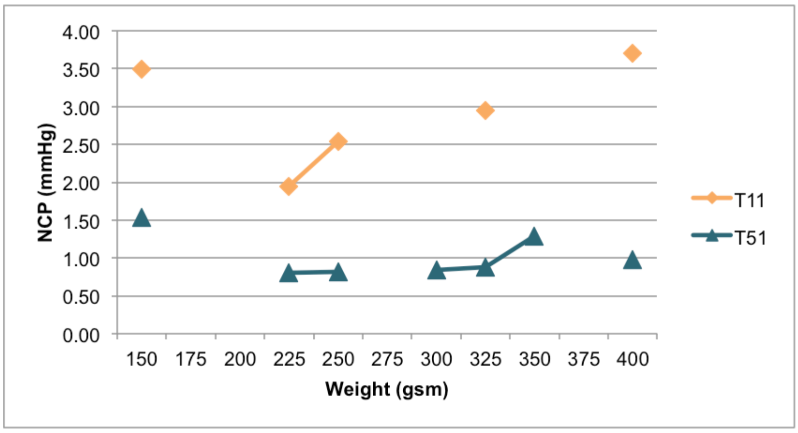


Figure 9.20: NCP at T11 and T51 for different fabric weight properties

9.6.4 Effects of Stitch Parameters on Virtual Pressure

The effects that variations in the two stitch parameters stitch constant and shrinkage had on virtual pressure values were recorded. This was particularly interesting since pressure levels at the seams were extremely high in all virtual fit simulations.

It is apparent from Figure 9.21 that the maximum pressure increased almost linearly with increasing stitch constant up to a stitch constant of 600g/cm. The maximum pressure of the NCP map was likely the pressure at the seam, as all seams were presented in red in the NCP maps. These pressure values were extremely high, especially when considering that the pressure values at location T131 (wrist) recorded on the same NCP map ranged from 3.2 to 6.0mmHg (refer Figure 9.22). This indicated that the effect of stitch constant on virtual pressure was comparatively small when measured centrally on a garment panel.

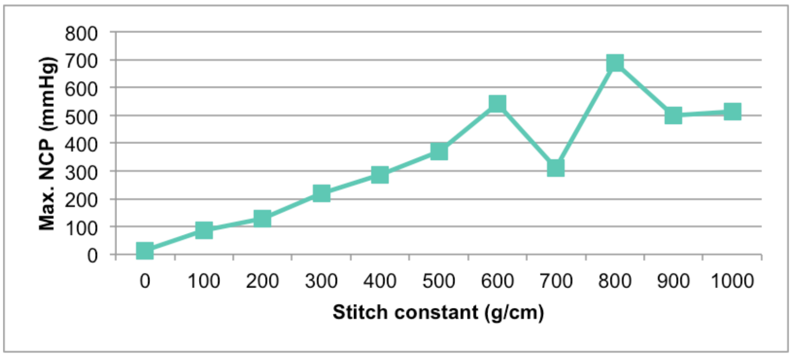


Figure 9.21: Maximum NCP for different fabric stitch constant properties

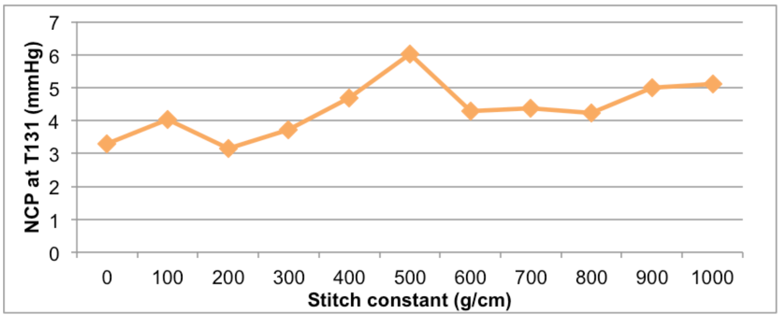


Figure 9.22: NCP at T131 for different fabric stitch constant properties

Pressure levels at T131 increased fairly linearly with growing stitch shrinkage levels up to a shrinkage level of about 70-80% after which point pressure levels decreased sharply (Figure 9.23). There was no substantial difference between the NCP-shrinkage curves with the two different stitch constant settings for PMs at T131, but maximum NCP values varied substantially (refer Figure 9.24).

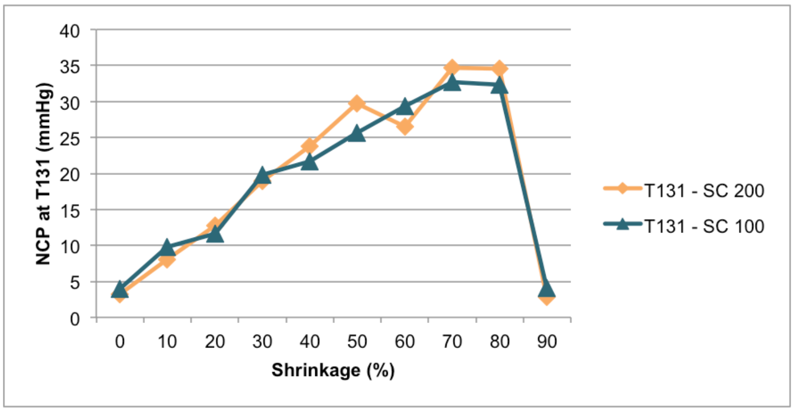


Figure 9.23: NCP at T131 for different shrinkage properties (SC 200: stitch constant 200g/cm; SC 100: stitch constant 100g/cm)

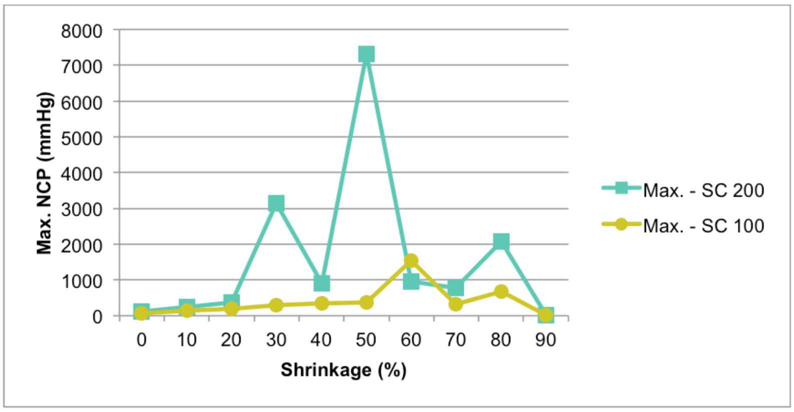


Figure 9.24: Maximum NCP for different shrinkage properties (SC 200: stitch constant 200g/cm; SC 100: stitch constant 100g/cm)

The fact that virtual pressures at the seams were extremely high in all virtual fit simulations is contrary to the realistic behaviour of pressures at seams. Whilst Allsop (2012) reported pressure drops under seams of male compression tops on a mannequin using a Tekscan (Tekscan, Inc., South Boston, MA, USA) measurement device, this study could not identify substantial differences in pressures under seams compared to no seams of the SCGs under investigation on a mannequin using a PicoPress® (Microlab, Padova, Italy) measurement device (refer 7.3.2.3).

Edge force is another parameter that defines stitches in Optitex. Both edge force and stitch constant are affected by the stretch properties of the fabric to be 'sewn'. As a consequence, any recommendations of actual values for stitch parameters given by Optitex are meaningless. Apart from assessing the appearance of the simulation with certain stitch settings, it is currently difficult to know which stitch settings are the most realistic from a technical point of view as there are no clear links between physical stitch properties and the stitch parameters used in Optitex. Future developments in 3D CAD need to address this issue.

9.7 Virtual Wearer Trials

To assess the feasibility of using the NCP map in Optitex as a tool to predict pressures, the WTs conducted in Study 3 of Phase II were repeated virtually. For this purpose, the SCG patterns from Study 2 were virtually fitted to the 15 remodelled body scan avatars. The pressure map tool of the 3D CAD programme was then used to record virtual PMs from the NCP map, which were compared to the in vivo PMs obtained in Study 3.

9.7.1 Settings for Virtual Wearer Trials

After many different simulation trials, the fabric parameters that resulted in the best visual simulation across all 15 body avatars and were believed to be the most representable of the actual physical fabric properties were chosen for the virtual WTs. The selected fabric settings are presented in Table 9.8. The Optitex FTU fabric results were used for most panels. The stretch values, thickness and weight of some panels were adjusted to more realistically represent the properties of the back waistband (Fabric B), the side panels of the tights (Fabric C and D) and the centre back panel of the top (Fabric D). Only the thickness and weight were adjusted for the waist panels of the top (Fabric F), as stretch properties were very similar to Fabric A.

Table 9.8: Fabric settings for virtual wearer trials

Garment Panels	Fabric Settings							
	Bending (dyn·cm)		Stretch (gf/cm)		Shear (gf/cm)	Friction[a]	Thick-ness (cm)	Weight (g/m²)
	X	Y	X	Y				
Back Waistband - tights	2.46	10.91	368.66	500	84.4	0.34	0.07	320.8
Side panels - tights	2.46	10.91	215	310	84.4	0.34	0.06	250
Centre back - top	2.46	10.91	190	310	84.4	0.34	0.05	240
Waist - top	2.46	10.91	190.29	285.61	84.4	0.34	0.06	188

Garment Panels	Fabric Settings							
	Bending (dyn·cm)		Stretch (gf/cm)		Shear (gf/cm)	Friction[a]	Thick-ness (cm)	Weight (g/m²)
	X	Y	X	Y				
All other panels	2.46	10.91	190.29	285.61	84.4	0.34	0.05	228.67

a: no unit provided by Optitex

It was not clear which settings were the most realistic for the three stitch parameters edge force, stitch constant and shrinkage, as there is no direct link to physical stitch properties. Pressure levels at the seams were extremely high in initial simulations and stitch constant had a large effect on pressure levels. Consequently, two different stitch settings were selected as presented in Table 9.9. Pressure analyses were conducted for each of these stitch settings, hereafter referred to as simulation settings A and B.

Table 9.9: Stitch settings for virtual wearer trials

Stitch settings	Stitch Settings A		Stich Settings B	
	Tights	Top	Tights	Top
A-seam and flat seams	Flatlock 0/100/0	Flatlock 0/100/0	Flatlock 0/50/0	Flatlock 0/50/0
Bottom hem	Lockstitch double needle 30/200/0, folded	Lockstitch double needle 30/50/4	Lockstitch double needle 30/50/0, folded	Lockstitch double needle 30/50/4
WB lower attachment	4-thread overlock 0/100/0	N/A	4-thread overlock 0/50/0	N/A
WB top (stitched to self)	Lockstitch single needle 0/100/0	N/A	Lockstitch single needle 0/50/0	N/A
Neck hem	N/A	Lockstitch double needle 0/100/0	N/A	Lockstitch double needle 0/50/0
Sleeve hems	N/A	Lockstitch double needle 30/200/0, folded	N/A	Lockstitch double needle 30/50/0, folded

Values represent Optitex stitch parameters: edge force (gf/cm) / stitch constant (g/cm) / shrinkage (%)

The resolution settings were kept as 1cm for all simulations as per the default setting. The time step setting of the global simulation settings was changed to the lowest value, 0.01s, as, according to Optitex (EFI Optitex, 2011), it leads to more accurate simulation results. This meant that computation times were slightly longer, however, quality of the simulations was a priority of this study. All other global simulation settings were kept as default for stitch settings B. However, for stitch settings A the spring stitch constant had to be changed to 400 to be able to come up with satisfactory simulations.

The waistband of the compression tights and the hem of the compression top featured elastic bands. Optitex recommended the use of 4gf/cm edge force, 100g/cm stitch constant and 4% shrinkage for swimwear bottoms with elastic bands. However, these settings resulted in failed simulation when applied for the elastic at the hem of the compression top. Simulations also failed for the following stitch settings at the waistband: 10/100/0, 20/200/0 and 4/200/0 (edge force/stitch constant/shrinkage). However, they worked for settings 4/150/0 and 10/150/0 at the waistband.

9.7.2 Reliability Check

Whilst working with Optitex, it became apparent that there were problems with the reliability of garment simulations. When the same Optitex pattern files were simulated on the same body avatars using the same computer and identical settings at different occasions, the results appeared to vary. This led to the decision to conduct a reliability check with the 15 body avatars. The results of the reliability check are presented in Appendix PP.

Most simulations resulted in exactly the same 3D representation when re-simulated, however, there was a substantial number of simulations that had differences in the appearance of the garment on the body and the way the cloth was simulated. This was especially apparent at the wrists and ankles, where there were variations in the simulations of the excess fabric. In a number of cases the repeat simulation even resulted in failed simulations. No comments or explanations for these issues were provided, when this was brought up with an Optitex consultant.

The tension and NCP maps were checked and the minimum and maximum values compared. It was found that the minimum and maximum tension and NCP values stayed constant when using the same simulation settings. However, it was noted that the tension and NCP values changed when the garment panels were very slightly moved on the body avatar prior to simulation. It was further identified that simulations of individual garments differed compared to simulations of multiple garments on the body avatar. For example, in some cases the simulation of the compression top worked on its own, but failed when simulated together with the tights, even though collision of the two garments was avoided.

To work around this problem it was attempted to save the simulated garment as a cloth file in the Optitex cloth file format (.clt). It was believed that the reliability problems would not be present with cloth files as these are simply dragged and dropped onto the body avatar without re-simulating the garment. However, it was impossible to drag both cloth files of the tights and top on the mannequin at the same time and in addition the pressure map was not working on a cloth file making the feature useless for this study.

Reliability is a key issue when attempting to use a 3D CAD programme as a tool for technical and scientific purposes and needs to be addressed by 3D CAD developers. The results from the visual reliability check are problematic and make the successful application of Optitex in the apparel industry highly questionable, as there would be high inter- and intra-operator variability. This represents a major limitation of Optitex, which has not previously been identified. However, since there were no differences between pressure and tension values of repeat simulations, the programme could still be used for the virtual WTs of this study.

9.7.3 Simulation Results

Figure 9.25 shows a comparison of the virtual and real fit of the SCGs worn by one of the WT participants. The visual representation of the virtual fit appeared to be realistic with seams located at the correct positions. Images of all 15 final simulations of the virtual WTs can be found in Appendix QQ.

Figure 9.25: Virtual fit and real fit of Skins A400 compression garments: a) front view; b) back view; c) left side view; d) right side view

9.7.4 Virtual Pressure Analysis

Only 13 participants were included in the analysis of pressure, as two participants each for the tights and top had been outside the available size range. PM locations at the ankle (B1, B2), wrist (T13) and chest (T6) were excluded from the pressure analysis due to simulation issues at these locations. It was believed that the gaps in the underarm area of some simulations could affect chest measurements. Furthermore, PM points B8 and T10 were eliminated, as they were hard to identify on the body avatar and the neck area was neglected (T7, T8). This left six PM locations on the tights and eight on the top for the virtual pressure analysis as listed in Table 9.10 (also refer Appendix N).

Table 9.10: PM locations included in the virtual pressure analysis

Tights	Top
B31: Calf at maximum girth	T11: Hem at centre front
B41: 5cm above upper border of patella	T21: 5cm above navel
B51: Midway along thighbone	T31: Front oblique
B61: Gluteus maximus at greatest projection	T41: Waist at side
B71: 5cm below waistband seam at side	T51: Shoulder blade 10cm down from neckline
B91: Waistband centre front	T91: Top of shoulder 5cm from neckline
	T111: Inner biceps at maximum girth
	T121: Inner forearm at maximum girth

Appendix RR shows the NCP maps of the 13 body avatars included in the virtual pressure analysis. NCP maps with pressure levels set at maximum 30mmHg were included for each avatar to better illustrate the pressure distribution across the body. Like in the initial simulation trials, pressure levels at the seams were extremely high (i.e. red) on all avatars. When recording pressure values from the NCP map, it became apparent that pressure values varied extensively when slightly moving the curser across the body avatar. This is not the case on a real garment and is a limitation of the NCP map. Three measurements were taken at each location to counteract this limitation.

Table 9.11 presents the results of the virtual PMs for simulation settings A and B of the compression top and tights.

Table 9.11: NCPs for simulation settings A and B

PM Location		Simulation settings	*n*	NCP (mmHg)				
				Range	Min.	Max.	Mean	SD
Top	T11	A	13	3.76	2.03	5.79	4.30	1.08
		B	13	6.31	0.58	6.89	3.62	1.97
	T21	A	13	4.84	0.05	4.89	1.67	1.47
		B	13	3.72	0.00	3.72	1.32	1.12
	T31	A	13	5.06	0.02	5.08	1.57	1.53
		B	13	4.79	0.28	5.07	1.44	1.49
	T41	A	13	8.02	1.40	9.42	5.16	2.49
		B	13	5.99	0.84	6.83	4.48	2.01
	T51	A	13	2.78	0.43	3.21	1.58	0.83
		B	13	3.08	0.61	3.69	1.89	1.11
	T91	A	13	26.90	4.91	31.81	13.37	6.80
		B	13	27.04	1.57	28.61	10.99	6.68
	T111	A	13	8.83	0.61	9.44	5.16	3.18
		B	13	11.02	0.31	11.33	5.56	4.01
	T121	A	13	13.82	1.18	15.00	7.55	4.16
		B	13	9.41	2.51	11.92	7.34	3.29
Tights	B31	A	13	21.86	20.00	41.86	26.99	5.55
		B	13	16.93	14.10	31.03	22.25	4.47
	B41	A	13	11.87	10.14	22.01	15.57	3.36
		B	13	142.75	12.87	155.62	25.84	39.04
	B51	A	13	14.35	10.21	24.56	16.71	4.04
		B	13	13.05	9.18	22.23	16.50	3.98
	B61	A	13	13.21	9.78	22.99	13.02	3.78
		B	13	10.18	7.55	17.73	11.98	3.17
	B71	A	13	36.31	0.13	36.44	9.56	8.89
		B	13	16.72	0.42	17.14	8.58	4.33
	B91	A	13	8.19	0.02	8.21	3.39	2.82
		B	13	11.50	0.09	11.59	4.60	3.51

SD = standard deviation

The lowest mean virtual pressure values recorded on the compression top were at locations T21 (5cm above navel), T31 (oblique) and T51 (shoulder blade), whilst the highest mean virtual pressure was recorded at location T91 (top of shoulder). Like in vivo PMs, the virtual pressure values recorded on the compression tights were generally higher with an overall mean virtual pressure level of 14.2mmHg (simulation A) and 15.0mmHg (simulation B) compared to 5.1mmHg (simulation A) and 4.6mmHg (simulation B) of the top. The lowest mean pressure on the compression tights was measured at B91 (waistband) and the highest pressure at B31 (calf) and B41 (knee).

Wilcoxon signed-rank tests (Appendix Table SS-1) revealed that there were no statistically significant differences in pressure values between simulation settings A and B recorded on the compression tights or top, except for location B31 (calf, $Z = -3.18$, $p = 0.001$, $r = -0.88$). The virtual pressure at this location was significantly higher with simulation settings A compared to simulation settings B. The compression tights feature several seams at the calf, which could be the reason why virtual pressures were affected by the different stitch settings between simulation settings A and B at this location.

During the virtual WTs not only the pressure values from the Optitex NCP map, but also the tension values from the Optitex tension map tool were recorded for each simulation in an attempt to assess if the Optitex tension map could support the prediction of in vivo pressures applied by SCGs. The recorded tension values are listed in Table 9.12.

Table 9.12: Tension for simulation settings A and B

PM Location		Simulation settings	N	Tension (fg/cm)				
				Range	Min.	Max.	Mean	SD
Top	T11	A	13	24.01	69.85	93.86	83.72	6.49
		B	13	22.99	72.66	95.65	85.40	6.81
	T21	A	13	34.07	36.76	70.83	53.93	12.14
		B	13	27.86	37.67	65.53	50.74	9.07
	T31	A	13	39.57	26.18	65.75	45.15	10.64
		B	13	36.88	29.49	66.37	47.02	10.64
	T41	A	13	67.26	15.92	83.18	48.63	16.92
		B	13	59.50	11.94	71.44	49.21	17.15
	T51	A	13	26.27	9.14	35.41	23.67	7.97
		B	13	27.49	15.75	43.24	29.81	8.48
	T91	A	13	100.93	64.30	165.23	99.27	26.29
		B	13	76.67	58.43	135.10	86.47	19.63
	T111	A	13	49.70	11.48	61.18	32.32	16.84
		B	13	51.61	10.49	62.10	30.58	17.33
	T121	A	13	109.57	19.65	129.22	64.93	34.29
		B	13	72.56	14.76	87.32	55.39	25.24
Tights	B31	A	13	90.05	200.99	291.04	235.35	32.43
		B	13	95.11	186.41	281.52	221.76	35.94
	B41	A	13	77.13	102.30	179.43	141.49	25.50
		B	13	80.80	121.07	201.87	158.47	28.47

PM Location	Simulation settings	N	Tension (fg/cm)				
			Range	Min.	Max.	Mean	SD
B51	A	13	92.47	179.14	271.61	229.07	30.73
	B	13	87.36	181.27	268.63	226.90	31.21
B61	A	13	79.35	155.71	235.06	192.50	25.64
	B	13	64.83	149.69	214.52	179.96	20.99
B71	A	13	53.63	107.84	161.47	133.64	14.30
	B	13	40.58	118.90	159.48	134.91	13.57
B91	A	13	66.45	72.10	138.55	106.69	17.72
	B	13	69.53	79.36	148.89	117.25	20.50

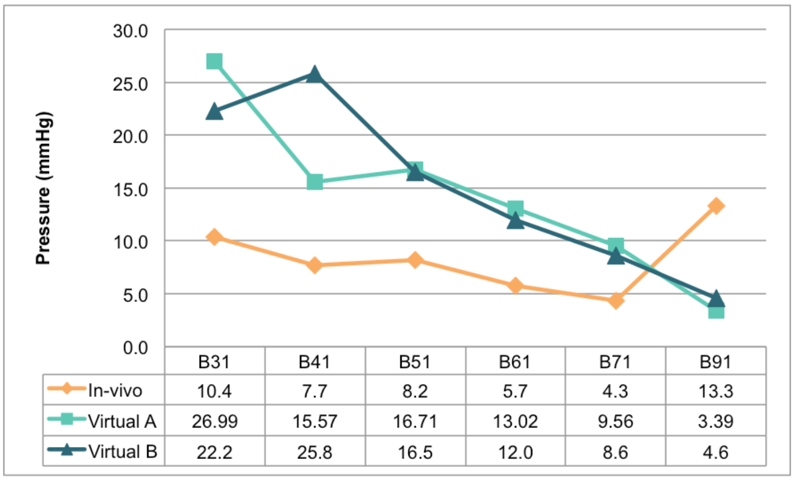
Tension values appeared to be more affected by changes in stitch parameters than NCP values. However, variations in tension levels were random with values increasing or decreasing from simulation settings A to B depending on the PM location. Wilcoxon signed-rank tests (refer Appendix Table SS-2) revealed that there were significant differences at measurement locations B31 (calf, $Z = -2.55$, $p = 0.011$, $r = -0.71$), B41 (above knee, $Z = -2.76$, $p = 0.006$, $r = -0.77$), B61 (gluteus maximus, $Z = -3.18$, $p = 0.001$, $r = -0.88$) and B91 (waistband, $Z = -3.11$, $p = 0.002$, $r = -0.86$) between virtual tension values for simulation settings A and B. Tension levels were significantly lower at the calf and the gluteus maximus with simulation settings B, whilst tension levels at the knee and waistband were significantly higher. There were also significantly different tension values at measurement locations T11 (hem, $Z = -2.41$, $p = 0.016$, $r = -0.67$), T51 (shoulder blade, $Z = -3.18$, $p = 0.001$, $r = -0.88$) and location T91 (top of shoulder, $Z = -3.18$, $p = 0.001$, $r = -0.78$) of the compression top. Tensions at the hem and top of shoulder were higher with simulation settings B, whereas tension at the shoulder blade was lower.

Significant correlations between the NCP and tension maps were only identified at the biceps (T111) and forearm (T121) for both simulation settings. Interestingly, there was also a strong, significant correlation between virtual pressure and tension at T111 and biceps circumference. Reasons for these correlations could be related to the smaller diameter of the arms compared to the rest of the body. Existing research (Macintyre et al., 2004; Macintyre, 2007) has reported that the use of Laplace’s Law is not suitable for circumferences below 30cm.

9.7.5 In Vivo vs. Virtual Pressure

The mean in vivo and virtual PMs for simulation settings A and B are presented in Figure 9.26 and Figure 9.27 for the compression tights and top, respectively. Overall, there was a bigger difference between mean virtual and in vivo pressure values of the tights than the top. Pressure distribution of virtual and in vivo pressures followed a similar pattern across the compression top with exception of T91 (top of shoulder 5cm from neckline), where there was a significant difference in pressure levels. Existing research (Allsop, 2012) has reported that the top of the shoulder was one of the PM locations with the highest pressure both measured on compression tops on a male mannequin and measured on a pressure map in 3D CAD. However, this study found that the in vivo PM at the top of the shoulder did not vary substantially from other PM locations. Pressure levels at the top of the shoulder were only slightly higher than pressures at the hem (T11) and forearm (T121) for the sample used in this study (n = 13). When considering all WT participants, pressures at the forearm were slightly higher than pressures at the top of the shoulder. However, the virtual PMs at the top of the shoulder were clearly higher than pressure values at all other PM locations. Since both the Optitex system and VStitcher (Browzwear Solutions Pte Ltd., Singapore) used by Allsop (2012) found high pressure values at the top of the shoulder, it could mean that the garment simulation overestimates pressure at this location.

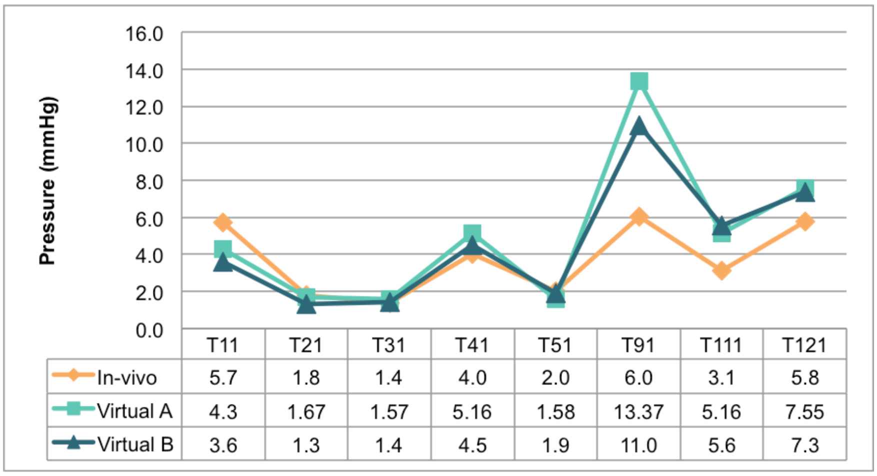
There were significant differences between virtual and in vivo pressures at all locations on the compression tights as identified by Wilcoxon signed-rank tests (refer Appendix Table SS-3). Virtual pressures were generally higher than in vivo pressures. The waistband (B91) was the only PM point on the tights where virtual pressures were lower than in vivo pressures. This is likely caused by poor simulation of garment components. The real garment featured a strong 39mm elastic band at the waistband, which applied a higher level of pressure to the underlying body. Optitex was unable to realistically simulate this. It is also apparent that the virtual pressures A and B were very similar to one another, but varied substantially at location B41 (5cm above upper border of patella). When measuring in vivo pressure at B41 the location was determined by palpation, however, it was difficult to locate the exact measurement point on the body avatars, which could have resulted in the pressure variations.



	B31	B41	B51	B61	B71	B91
In-vivo	10.4	7.7	8.2	5.7	4.3	13.3
Virtual A	26.99	15.57	16.71	13.02	9.56	3.39
Virtual B	22.2	25.8	16.5	12.0	8.6	4.6

Figure 9.26: Mean in vivo and virtual pressures measured on tights (*N* = 13)

There were no significant differences in in vivo and virtual pressure levels of the top with exception of location T91 (A: $Z = -2.83$, $p = 0.005$, $r = -0.78$; B: $Z = -2.48$, $p = 0.013$; $r = -0.69$).



	T11	T21	T31	T41	T51	T91	T111	T121
In-vivo	5.7	1.8	1.4	4.0	2.0	6.0	3.1	5.8
Virtual A	4.3	1.67	1.57	5.16	1.58	13.37	5.16	7.55
Virtual B	3.6	1.3	1.4	4.5	1.9	11.0	5.6	7.3

Figure 9.27: Mean in vivo and virtual pressures measured on top (*N* = 13)

In order to determine the relationship between the 13 in vivo and virtual pressure values at each PM location, Spearman's correlations were run. There were no significant correlations between in vivo and virtual pressure values at any of the PM locations for simulation settings A or B, except at location T51 (shoulder blade) for simulation setting B (Table 9.13). This indicates that the virtual pressure values provided by the NCP map are not realistic representations of the in vivo pressures applied by SCGs.

Table 9.13: Correlation between in vivo and virtual pressures

	Measurement Point	Simulation Settings A		Simulation Settings B	
		Spearman's rho	*p*	Spearman's rho	*p*
Tights	B31	-0.09	0.763	0.05	0.862
	B41	-0.21	0.502	-0.06	0.846
	B51	0.09	0.762	0.21	0.494
	B61	0.05	0.880	-0.04	0.910
	B71	0.26	0.384	0.28	0.358
	B91	0.02	0.950	-0.07	0.822
Top	T11	-0.04	0.903	-0.52	0.068
	T21	0.18	0.564	0.46	0.118
	T31	0.08	0.807	-0.10	0.736
	T41	0.51	0.074	0.10	0.748
	T51	0.34	0.251	0.70	0.008*
	T91	-0.40	0.180	0.02	0.950
	T111	0.29	0.340	0.17	0.571
	T121	0.14	0.638	-0.02	0.957

** significant correlation*

Correlation between in vivo pressure and virtual tension

No statistically significant correlation between in vivo PMs and virtual tension values could be identified for simulation settings A and B of the compression tights (refer Table 9.14). The same is true for the compression top with the exception of locations T11 (hem at centre front) for simulation settings A and T41 (waist) for simulation setting B.

Table 9.14: Correlation between in vivo pressures and virtual tension values

	Measurement Point	Simulation Settings A		Simulation Settings B	
		Spearman's rho	*p*	Spearman's rho	*p*
Tights	B31	0.50	0.085	0.18	0.550
	B41	0.45	0.126	0.47	0.105
	B51	0.09	0.762	0.54	0.059
	B61	0.28	0.363	0.19	0.544
	B71	0.50	0.083	0.45	0.122
	B91	0.29	0.340	0.27	0.375
Top	T11	0.61	0.028*	0.52	0.067
	T21	0.55	0.05	0.38	0.195
	T31	0.28	0.350	0.06	0.855
	T41	0.35	0.243	0.64	0.018*

Measurement Point	Simulation Settings A		Simulation Settings B	
	Spearman's rho	*p*	Spearman's rho	*p*
T51	0.47	0.105	0.33	0.279
T91	-0.06	0.657	0.06	0.843
T111	0.20	0.521	-0.04	0.906
T121	0.10	0.739	-0.03	0.914

** significant correlation*

Correlation between virtual pressure/tension and body measurements

As there were no correlations between in vivo and virtual pressures, it was assessed if a relationship between the virtual pressure and tension measurements and body measurements could be identified. This could support a pressure prediction process. Spearman's correlations were run to assess the relationships between the NCP and tension maps and body circumference measurements of the avatars. There were no correlations between NCP values and body measurements at the respective measurement locations except at measurement location T111. There were moderate correlations between NCP at T111 and biceps circumference (A: $\rho = 0.62$, $p = 0.025$; B: $\rho = 0.67$, $p = 0.013$), as well as strong correlations between virtual tension at T111 and biceps circumference (A: $\rho = 0.71$, $p = 0.007$; B: $\rho = 0.71$, $p = 0.007$).

Correlation between virtual pressure and body slices

No correlations could be detected between the NCP values at B31 and B61 and the calf and gluteus maximus slice circumferences that were extracted with the 3D body scan software in Phase II.

Correlation between virtual pressure/tension and garment stretch percentage

Spearman's rho correlation tests were run to assess whether the Optitex NCP and tension maps correlated with the garment stretch percentage values calculated in Phase II. Table 9.15 presents the identified correlations at significance level $p < 0.05$.

Table 9.15: Significant correlations between NCP/virtual tension and garment stretch percentage

Correlation	PM Location	Simulation settings	Spearman's rho	Sig.
Garment stretch at hip – virtual tension	B61	A	0.77	0.002
		B	0.74	0.004
Garment stretch at hip - NCP	B71	A	0.60	0.030
		B	0.65	0.017
Garment stretch at mid-thigh - virtual tension	B51	A	0.82	0.001
		B	0.75	0.003
Garment stretch at calf - NCP	B31	A	0.64	0.018
		B	-	-
Garment stretch at calf - virtual tension	B31	A	0.56	0.049
		B	-	-
Garment stretch at hip - virtual tension	T11	A	0.92	< 0.001
		B	0.73	0.005
Garment stretch at biceps - NCP	T111	A	0.73	0.005
		B	0.73	0.005
Garment stretch at biceps - virtual tension	T111	A	0.73	0.005
		B	0.71	0.006
Garment stretch at forearm - NCP	T121	A	0.68	0.011
		B	-	-

No correlations could be detected at the waist (T41) and knee (B41). At the calf (B31) and forearm (T121) correlations could only be detected for simulation settings A, not B. Some correlations were also only detected between the garment stretch percentage and the tension map, whilst others were detected between the garment stretch percentage and NCP map. This indicates that there are no correlations between the tension and NCP maps. Spearman's rho correlation tests confirmed this assumption for the compression tights with exception of measurement location B91 (waistband, $\rho = 0.67$, $p = 0.013$) only for simulation settings A. Spearman's rho correlation tests revealed that there were strong correlations at significance level $p < 0.01$ between the NCP and tension maps of the compression top at locations T41 (waist, $\rho = 0.75$, $p = 0.003$), T111 (biceps, $\rho = 0.86$, $p < 0.001$) and T121 (forearm, $\rho = 0.85$, $p < 0.001$) for simulation settings A and T21 (5cm above navel, $\rho = 0.74$, $p = 0.004$), T111 (biceps, $\rho = 0.96$, $p < 0.001$) and T121 (forearm, $\rho = 0.85$, $p < 0.001$) for simulation settings B.

Significant correlations could be identified between garment stretch values at the calf and virtual pressure values of simulation settings A, however, there were no significant correlations between garment stretch and virtual pressure values of simulation settings B. There were further significant differences in pressure levels at the calf (B31) between simulation settings A and B. The only differences between simulation settings A and B are variations in stitch parameters. This highlights the impact that stitch parameters can have on NCP and calls attention to the importance of accurate stitch parameters. Overall, there was no clear relationship between garment stretch and virtual pressure and tension that could be utilised to predict pressures.

9.8 Evaluation of Optitex as Tool for Pressure Prediction

The evaluation of Optitex as a tool that can be employed to predict pressures in the design phase of SCGs is based on the findings of this chapter. With real-world application in mind, the evaluation focuses first on the feasibility of the virtual fit process to be applied in the practical design environment and then on the technical aspects of predicting garment pressures.

9.8.1 Practicability of Pressure Prediction Process

A successful virtual fit process depends on the accurate 3D representation of a garment including the physical properties of the fabrics and components (e.g. elastic webbings) used in the garments as well as construction methods applied to join garment panels and components. Fit, however, is not just defined by the garment, but by the interaction of the garment and the wearer’s body. Thus, it is just as important to have an accurate representation of the wearer’s body in virtual fit. When designing for specific body dimensions, the existing parametric models in Optitex and most other 3D CAD programmes are not suitable to create a fully accurate body avatar due to limitations in body measurement adjustments of the parametric models. It is, therefore, necessary to import body scan data. Body scan data files can be imported in OBJ-file format, however, avatars based on raw body scan data are likely to require remodelling. Most 3D body scanners cannot capture every single part of the body due to the scanning position of the body and the number, location and angle of the scanning sensors. In this study, data occlusion was especially prominent in the underarm and in some cases the crotch areas of the body. Additionally, there were uneven body contours where the scanner had picked up additional points that were not part of the body. As a consequence, it was impossible to directly use the body scan avatars. The files had to be retopologised to remove ‘webbing’ in the underarm and crotch areas and to smoothen the body surface. This required the work of a computer expert, as there were no established methods for remodelling body scan files and it required advanced knowledge of specialist 3D programmes. This is the first major obstacle in the application of 3D CAD for pressure prediction. Whilst this is not a shortcoming of Optitex, but the body scanner, Optitex could mitigate this issue by enabling a more detailed, independent modification of the body measurements of parametric models in the software. Ideally, one would want to import an extensive list of body measurements extracted from the body scan and an avatar would be adjusted based on these measurements. Whilst still not fully representative of the body, it would be a solution that is practicable in a design environment where custom designs are made or where there is no access to a computer expert capable of remodelling body scan avatars.

The actual virtual fit workflow in Optitex is not too demanding for designers familiar with other 2D/3D CAD programmes, however, the virtual ‘stitching’ process may require some practice. This is especially true for the ‘stitching’ of complicated garments, such as garments with many pattern pieces and multiple fabric layers. Garment panels with double fabric panels were left out in this study, as it was impossible to ‘stitch’ these. This would not be acceptable in a practical environment.

In order to obtain a technically accurate virtual fit simulation, the designer is required to select various simulation parameters. With no direct links between the simulation parameters and real garment properties, the designer is left to either use the Optitex default options or make random, subjective selections.

The most important parameters for a realistic garment simulation are fabric parameters. Up to version 10 of Optitex PDS it was possible to convert fabric test results obtained from FAST and KES-F into Optitex fabric parameters with a built-in fabric converter tool. It is a big limitation that the software no longer supports the use of objective fabric evaluation systems, but instead uses its own Optitex FTU, which has no accreditation from an independent standardisation body. Optitex do not provide details about testing standards, likely due to commercial reasons.

Whilst it is possible to send fabrics to Optitex and have them tested with the FTU or even to purchase an in-house FTU, this involves substantial cost for the user, whilst the results of the FTU are meaningless to the user. This represents another major obstacle in the implementation of the pressure prediction process in the practical design environment. Optitex does not allow designers the flexibility to change fabrics and observe changes to pressure application in the NCP map, as they are unable to input objective fabric properties.

In addition to the technical simulation parameters, the garment simulations in this study frequently resulted in failure or had fabric gaps or other simulation problems. Achieving acceptable simulations was a long process of trial and error as well as approximations. However, when using virtual fit technology for technical evaluation purposes, precision is vital. Furthermore, users working in a fast-paced design environment would not have the time to extensively tweak the simulation in order to obtain an acceptable simulation result. The process is very unpredictable. Porterfield and Lamar (2016) reported that obtaining a successful and complete simulation took 2 to 23 attempts.

It was further found that minimal variations in garment placement on the body prior to simulation led to variations in NCP values. Since garment panel placement varies slightly across different users, it is likely that the NCP map of a garment created by one user would differ from the NCP map of the same garment simulated by a different user, making use of the NCP map for technical evaluation within a commercial environment difficult. This is further exacerbated by the fact that this study identified reliability issues with repeat simulations.

It also became apparent that there was a difference in simulating the SCGs individually or together, i.e. the compression top over the compression tights. There were several cases where the simulation of the top worked on its own, but failed when simulated over the tights and vice versa. It was found that it is especially critical to avoid clashes of the side seams and the body avatar when simulating the top over the compression tights.

Based on the findings of this study, it is rather unsurprising that 3D CAD software has a low adoption rate in the apparel industry. It is a cumbersome process to achieve a successful virtual fit representation. Although it has to be acknowledged that some of the simulation problems described here are related to the negative fit of SCGs and the related high level of stretch of the compression tights and top. Most garments have positive ease, i.e. they are bigger than the wearer’s body, which facilitates draping them around a body avatar, as they do not have to the stretched extensively to fit around the body.

9.8.2 Pressure Prediction

This study measured the effects of different simulation settings and garment parameters on visual simulation results and pressure values in the Optitex NCP map in order to better understand these parameters and their relation to realistic garment properties, which would allow systematic manipulation of the parameters to create more realistic simulations. Whilst no conclusive remarks could be made about the relationship of the different settings and visual simulation and NCP values, it was clear that NCP values highly depend on the settings of the various simulation parameters. The fact that there are no clear links to real physical properties makes the use of NCP maps for pressure prediction problematic, as it is impossible to know which settings result in the most realistic garment simulation and associated NCP values.

The comparison of the virtual pressure values recorded from the NCP map and in vivo pressure values from the WTs in Phase II showed that there were no correlations between the virtual and in vivo pressures except at location T51 (shoulder blade). This led to the conclusion that for the settings used in this study the NCP map in Optitex is not capable of predicting in vivo pressure measurements. Based on the problems and limitations of the virtual fit process discussed in this chapter, this may not come as a surprise. However, it needs to be considered that it is difficult to take PMs at exact locations on the body avatar, as pressure readings in Optitex can only be taken by pointing the cursor at the location on the body avatar and reading the pressure value off the pressure scale. It is not possible to add any marks to the garments. Whilst three measurements were taken at each location to counteract this limitation, it could have had an effect on pressure readings. Though, it also highlights the difficulty in incorporating virtual fit in practical design environments.

One of the most important factors when using virtual fit for technical evaluation of garments, is the setting of simulation properties. The most important settings are the fabric and stitch parameters of the garments to be simulated. If virtual fit is to be used for technical assessments of garments, there needs to be more transparency by the 3D CAD software developers on how fabric properties are converted from one test system to another (Power, 2013). There needs to be a clear link between objective physical fabric properties and the parameters used for the simulation algorithm.

Stitch properties are an especially difficult area when it comes to simulation parameters, which has been neglected by current research. In this study, pressure levels at the seams of the simulated garments were extremely high. It was not possible to eliminate this problem by changing stitch parameter settings, which leads to the conclusion that it must be related to the high stretch of the garment panels. It, however, was not a realistic representation of the seams.

Stitch properties need to be adjusted according to fabric properties, since edge force and stitch constant are affected by the stretch properties of the fabric to be ‘sewn’. Apart from assessing the appearance of the simulation with certain stitch settings, it is currently difficult to know which stitch settings are the most realistic from a technical point of view.

The simulation of stitches and garment components (e.g. elasticated waistbands) is very limited in Optitex and most other 3D CAD programmes (e.g. VStitcher, AccuMark® 3D). This is a major shortcoming in virtual fit and limits current commercial 3D CAD programmes to visualisation of 3D garments for communication and marketing purposes. Until there is a stitch and components library or feature for input of meaningful technical parameters that can be related to physical fabric and garment properties, the NCP map of Optitex is unlikely to be suitable for objective technical assessments of garments or pressure prediction.

Another aspect to consider is that body avatars are solid objects in 3D CAD and therefore are not a realistic representation of the human body with its various tissue compositions (e.g. muscle mass, fatty tissue, bony prominences) with different levels of compressibility. As has been shown by existing research (Sawada, 1993), variations in body tissue affect pressure levels. This may mean that the use of solid body avatars may never accurately predict SCG-body-interface pressure, as garment pressure cannot compress the underlying avatar body the way it would real human bodies.

Whilst these findings are only valid for the particular settings applied in this study, the described problems with the simulation process and limitations of technical garment properties allow for the conclusion that current clothing-specific 3D CAD programmes are not practicable in a commercial design environment and cannot be used for technical evaluations of garments. It is believed that 3D CAD has a future in the design and product development of SCGs, but a lot of work is to be done in the development of more sophisticated virtual fit software systems before it would be of use in commercial technical design processes. There appears to be a problem with knowledge exchange among software developers and technical designers. Software developers need to understand the ‘language’ of textile and garment technologists and the practical needs of technical designers. There needs to be an understanding of the varying requirements of virtual fit for marketing and sales purposes and virtual fit for technical design. If 3D CAD is to be of use to technical designers, more focus on technical garment properties is required rather than on rendering and realistic visualisation of garments.

9.9 Chapter Conclusions

Chapter 9 assessed the feasibility of using the commercial 3D CAD software programme Optitex PDS 11 to predict pressures applied by SCGs to a body of known size in order to facilitate the design of SCGs with controlled pressure.

The study attempted to overcome known shortcomings of clothing-specific 3D CAD programmes by manipulating various simulation settings and assessing their effects on the visual simulation and virtual pressure levels in the NCP map. This was the first study to manipulate individual elements of fabric parameters, stitch parameters, resolution parameters and global simulation settings and assessed their impact on virtual fit. This detailed analysis did, however, not crystallise the logic between simulation settings and realistic garment properties, it rather highlighted further deficiencies of the Optitex 3D CAD technology, which pose a major barrier in the application of virtual fit for pressure prediction.

This study was also the first known study to compare absolute pressure values recorded from a pressure map to in vivo pressure values by virtually repeating the WTs conducted in Study 3 of Phase II. However, no correlations could be identified between virtual and in vivo pressures.

It was concluded that the technically realistic simulation of SCGs on body avatars is currently not possible due to technical shortcomings of the 3D CAD programme and a very cumbersome, unreliable simulation process that is not practicable. Future developments of commercial clothing-specific 3D CAD software should be based on collaborations between textile and garment technologists as well as computer scientists to develop 3D CAD programmes that realistically simulate garments on body avatars for technical garment evaluation. The following recommendations for future 3D CAD developments that improve virtual fit have emerged from this chapter:

- The study showed that there were problems with the reliability of the visual garment simulation. The virtual fit process needs to be reliable in terms of repeat simulations and inter-user reliability, as otherwise fit evaluations based on virtual fit made at different points in time or by different users could result in different design decisions.
- The study demonstrated that it is impossible to directly import 3D body scan avatars due to uneven surfaces and data occlusion in the underarm area, which required substantial expertise and time to remodel the body scan files. Hence, the use of built-in parametric models is more practicable. However, there needs to be more flexibility in the adaptation of body measurements. Ideally, avatar adjustment based on the import of detailed lists of body measurements obtained from body scanning should be supported. However, it needs to be considered that body models in 3D CAD are solid objects and thus cannot fully represent the human body with its variations in body tissue composition (e.g. muscle mass, fatty tissue, bony prominences).
- Future developments in 3D CAD should support the input of fabric and stitch parameters that have a clear relation to real physical fabric and stitch properties. This is an essential requirement to make virtual fit useful for technical garment evaluations, as this study has shown that changing fabric and stitch parameters affects pressure levels, however no logical relationship between the parameters and pressure levels could be identified. Current inputs of fabric and stitch parameters are meaningless to garment and textile technologists.
- In order to make 3D CAD practicable in industry, it would be useful to have a stitch and component library that is based on meaningful technical

parameters, so that fabric and stitch changes can be applied quickly and their effects on fit and pressure levels can be assessed in the simulation.

- The study identified variations in pressure maps when resolution and global simulation settings were changed. These settings should not affect pressure maps as pressure is defined by the relationship between the garment (fabric tension) and the body.

If 3D CAD programmes were capable of fulfilling the above points, they could be incorporated into the design process of SCGs and largely facilitate the design of SCGs with desired pressure specifications. This could lead to improved SCGs and allow consumers to make informed purchase decisions.

10 PHASE IV: SYNTHESIS OF FINDINGS TO DEFINE SPORTS COMPRESSION GARMENT DESIGN FRAMEWORK

10.1 Chapter Introduction

This chapter synthesises the key findings of the review of existing research (Chapters 2 and 3) and the primary research (Chapters 5 to 9) of this work and views these findings through three different lenses: 1) the process lens, 2) the user lens, and 3) the product lens. In Chapter 4, synthesis was defined as ‘putting elements together to a coherent whole to create new knowledge’ (refer Figure 4.2). This chapter puts the key findings of this work together and considers their implications for the design of sports compression garments (SCGs). Based on these findings, conceptual SCG design principles and a framework for the design development of SCGs are defined. The design framework is developed sequentially focusing first on the process, followed by the user, and lastly the product. Finally, the different perspectives are synthesized in the SCG Design Model, which supports the systematic design of SCGs to predetermined specifications. The chapter addresses Aim 6 of this research.

10.2 Synthesis of Key Findings

This work has highlighted that the design of SCGs differs from the design of conventional clothing and performance sportswear because the key element in the design of SCGs is the application of specific pressure levels to the body. Achieving the delivery of the desired pressure levels requires the input of garment and textile technologists, whilst judgements and decisions on pressure levels and distribution required for SCGs to function optimally demand the input from medical and sports researchers. SCG design development teams, thus, need to consist of a multi-functional team of experts.

10.2.1 Process Lens

A successful design hinges on the design team’s understanding of the end users’ needs and the ability to translate these needs into garment characteristics, following a rigorous design process. With no existing design processes for SCGs, the most appropriate approach is to follow the principles of functional clothing design since these processes involve a structured, problem-solving approach to design that is rooted in engineering practices (refer section 3.2.2).

Like any functional clothing design process, the design of SCGs needs to apply a user-centred approach that enables the fulfilment of stringent pressure, design and functional requirements within a given tolerance. It needs to consider all general concerns of performance sportswear, however, all design decisions and stages also need to consider their influence on pressure delivery. It is, therefore, critical that SCG design teams understand the effects that different design decisions have on pressure application. A design framework or model that optimises this decision-making would facilitate the design process and result in improved SCGs.

The basic elements that all functional clothing design processes have in common are: Problem definition and research, creative exploration and implementation with most processes including at least five stages: 1) Research, 2) Problem definition, 3) Idea generation, 4) Design development and 5) Evaluation, as defined by Watkins and Dunne (2015). In functional clothing design there is an emphasis on detailed research at the beginning of the design process to fully understand the design task on hand and the user and market needs. It is further important that the process is iterative. Based on the evaluation of a prototype, designers can repeat process steps to optimise the design.

In Chapter 9, the feasibility of applying three-dimensional (3D) computer-aided design (CAD) technologies into the design process of SCGs was assessed. The virtual fit capabilities of 3D CAD and particularly the built-in pressure maps offered a promising opportunity to facilitate the design process by predicting pressures in the design phase through simulation of SCGs on customised body avatars using the pressure map to evaluate pressure application across the body. Unfortunately, current commercial clothing-specific 3D CAD programmes are unable to realistically simulate technical garment properties, such as detailed fabric and seam properties. Consequently, the design process of SCGs needs to fall back onto the principles of Laplace’s Law and reduction factors to design SCGs to given pressure specifications. The accuracy of the pressure profile needs to be measured manually on human subjects using a pressure measurement (PM) device. This is vital, as pressure levels measured on mannequins can substantially vary from pressures measured on human bodies.

Overall, the design process for SCGs needs to follow a structured approach and focus heavily on the initial research stage and the definition of user- and sport-specific design and pressure requirements. Auxiliary user needs have to be fulfilled, but not at the expense of pressure delivery. Designers need to understand interrelations of different design decisions and pressure application.

10.2.2 User Lens

When observing the findings through the user lens, it became apparent that there are two aspects that make up the user: 1) the user as ‘consumer’, who makes consumption decisions and has feelings and perceptions about themselves, their bodies and SCGs, and 2) the user as ‘wearer’ with the primary concern of the human body and its relation to SCGs. Both aspects of the user were considered when synthesising the findings viewed through the user lens.

10.2.2.1 Wearer

SCGs have to be designed for the body dimensions and predominant body shape of the target user population. The human body cannot only be considered in static condition, but needs to be analysed in its dynamic near-environment, i.e. its interaction with the physical environment and potential other equipment during the sporting activity and use situation.

Since SCGs are designed for use in sport, ergonomic factors and mobility of the body need to be considered. Whilst fit and comfort are key human factors that have to be achieved by any SCG design, there are other user needs that vary in importance depending on the activity or sport and the commitment to the sport.

Adequate fit of SCGs directly affects pressure application and, consequently, needs to be a priority for any SCG design team. Optimal fit further ensures ergonomic comfort. Tactile comfort is another fundamental user need, whilst thermal comfort depends on the use environment (e.g. outdoors, indoors, likely temperatures). When designing whole-body SCGs, it is important to communicate the thermal and moisture wicking properties of the SCGs since findings indicate that overheating is a concern for some users that are used to less body coverage during exercise.

The way users wear SCGs is another important consideration in the design of SCGs. This includes an understanding of whether users prefer wearing SCGs as base layer under more loose-fitting clothes or as outer layer, as well as the wear frequency and duration. Understanding users' expectations and the role SCGs take in users' (sporting) lives is critical.

Whilst fit is a major concern both for pressure application and comfort, price needs to be considered when designing SCGs as it is a decisive point when purchasing SCGs. It is important to communicate the benefits of the product to the consumer in order to justify the generally higher price point compared to conventional performance sportswear. Evidence-based claims are more likely to convince consumers, however, brands need to stop selectively presenting the most beneficial studies to provide evidence of their functionality and provide a broad view of existing research on SCGs. With more consumers believing in the recovery-enhancing properties of SCGs and more evidence on the recovery-enhancing properties of SCGs, consumers are looking for evidenced claims. SCGs can have strong perceptual effects on wearers who believe in the garments' functionality with positive perceptions likely to support physiological effects of SCGs.

10.2.2.2 Consumer

The SCG consumer is viewed here as the user in her cultural environment and with individual aesthetic and expressive needs. The design of SCGs for females requires a balance between the functional garment aspects and aesthetically pleasing garments. The bias of this balance depends highly on the target users and needs to be researched at the start of the design process.

The findings from this study showed that satisfaction and belief in the functionality of SCGs are not necessarily related to exact PMs, but are more related to personal preferences and body satisfaction. Understanding consumers' needs for psychological comfort and their level of self-esteem is, therefore, important in the design of SCGs; on the one hand, to design SCGs that are flattering to the users' bodies and on the other hand, to communicate the design in a way that attracts and satisfies users.

This research has identified the following points to consider for the user-centred design of SCGs:

- It is important to understand users' expectations on SCGs and the role the garment will to play for the users.
- Users do not necessarily define pressure as their main need, but take it as a given when wearing SCGs. Their concerns are more related to comfort, fit and style of the garments.
- It is critical to design garments to the body dimensions of the target users since these can vary widely across different sports disciplines.
- Use situation-specific demands need to be analysed in detail to identify ergonomic and environmental demands on the SCGs.
- Along with functional needs, aesthetic and expressive needs of the user have to be considered and are likely to vary for different target users.
- The way SCGs are marketed to the user is likely to improve their perceptual effects, which could influence the functionality of the SCGs (e.g. placebo effect).

10.2.3 Product Lens

This study examined SCGs from a holistic viewpoint. SCGs were seen as functional garments; garments that are used as ergogenic aids, thus providing a function to the wearer. Because SCGs stem from the medical field, which is mainly concerned with the pressure treatment and utilises mainly compression stockings or simple tubular garments, important garment aspects have been neglected. There is currently very limited guidance on how to technically design compression garments (CGs) for the performance sports environment.

With functional clothing every element of the garment needs to have a purpose and be designed for optimal fit and - in the case of compression sportswear - optimal pressure distribution across the body. Fit and sizing as well as fabric properties are crucial for SCGs to apply specific pressure levels at key locations across the body (e.g. major muscle groups).

The desired effect of the product (e.g. hemodynamic, reduction of muscle vibration or improvement of proprioception) and related pressure requirements need to be clear at the start of the design phase as many design decisions affect pressure levels. Pressure is determined by complex interactions between multiple factors, such as fabric structures and properties, thermal and moisture regulatory properties, the size and shape of the SCG in relation to the wearer's body, nature, level and environment of the physical activity undertaken etc.. Many of these factors are not constant during wear and vary across different wearers and use situations. Hence, pressure levels are likely to vary during wear and across individuals within one size category. Whilst designers cannot control external factors, it is the task of the design team to keep pressure variations within a pre-determined tolerated range to achieve the desired effect. The biggest influences on pressure that can be controlled by the design team are fabric selection, pattern design and sizing. Just like conventional sportswear, SCGs need to support the body's physiological functions during exercise.

The pressure level and pressure profile needs to be defined based on the desired effect of the SCGs and type of sport and associated body movements. There is currently no defined optimal pressure level. It is likely to vary depending on the desired effect. Independent of the pressure level, pressure variations need to be within the defined acceptable range throughout the duration of wear, which is generally multiple hours and can be up to 12 hour when worn during recovery. The garment needs to be comfortable for the duration of this period.

The analysis of commercial SCGs showed that for the design of SCGs with controlled pressure it is essential to use high-quality fabrics and analyse anthropometric data of the target population in detail. There is a need for improved size charts that consider girth measurements.

10.2.3.1 Fabric Selection

Fabrics are an integral part of any garment. In SCGs, the importance of fabric selection is even more prominent as the physical properties and mechanical behaviour of fabrics affect pressure application. SCG patterns have to be designed based on fabric elastic properties, meaning that changing fabrics for a SCG results in a rework of the patterns for the garment. Hence, fabrics need to be analysed thoroughly prior to selection.

Elastic properties of fabrics are essential for the pattern design, however, how specific fabric mechanical properties, such as fibre, yarn and construction properties translate to pressure variations is not yet understood due to the complicated interactions between different fabric properties. Fabrics with excellent elastic recovery need to be selected to avoid pressure loss over multiple wear occasions.

The weight and structure of the applied fabrics depends on the use behaviour and environment. Fabric requirements are different depending on whether SCGs are worn as base layer or outer layer or whether the sports activity is taking place indoors or outdoors.

10.2.3.2 Pattern Design

Fit is critical for SCGs as it affects both compression and comfort, two aspects that can influence the wearer’s performance. Hence, it is vital to control fit of SCGs. Fit is vastly determined by the garment pattern. Pressure levels need to be controlled across the body, meaning that there is not much tolerance in fit and that garments need to be engineered with precision. The design of SCG patterns has different objectives than conventional pattern making. SCGs need to fit like a second skin and follow skin stretch during movement, whilst applying the pre-determined range of pressures.

There is currently no published research on the design of SCG patterns. Designing patterns for SCGs requires the input of experienced pattern cutters or garment technologists. Unlike conventional pattern cutting that works with a small number of body measurements and designs garments proportionally, the pattern design for SCGs requires a large number of body measurements, which are directly used to determine garment dimensions. Circumference measurements across the limbs need to effectively be taken every few cm in order to identify variations in shape, so that patterns can be designed to apply the desired pressures. Body dimensions of the sport-specific population need to be used to achieve adequate fit, since body dimensions and shapes can vary significantly across different sports disciplines. This can be achieved with a 3D body scanner.

The body measurements are then reduced by a factor that is determined by the desired level of applied pressure and the fabric's elastic and tension properties. It needs to be considered that when the same reduction factor is used on tubular CGs, the pressure applied to a smaller limb circumference is higher and the pressure decreases as the size of the limb increases (Laplace's Law). So reduction factors have to be calculated for each key body location.

Pattern panels for SCGs need to be engineered to the specific requirements of the body in action in the use situation. They are based on body shapes as different pattern panels are designed to either match muscle groups or areas of the body with increased demands on mobility (e.g. knee) or thermoregulation (e.g. underarm areas, centre back) so that fabrics with optimal properties can be used in these areas. Consequently, SCGs are often designed with more garment panels than conventional sportswear. A larger number of garment panels results in more seams to join the panels into a 3D garment. Garment panels need to be shaped so that seams, which need to be as flat as possible, are placed at strategic locations across the body for the specific sport activity, e.g. along lines of non-extension and not along major nerve endings, where seams can be irritating.

If the intention is to reduce muscle vibration and support targeted muscle groups, designing the shape of pattern pieces can be easier done in 3D on the body and then flattened to two-dimensional (2D) shapes. This is a process, which would benefit from the use of 3D CAD. However, as outlined in Chapter 9, current clothing-specific 3D CAD programmes lack substantial technical aspects. No known studies have attempted the 3D-to-2D pattern design in 3D CAD for SCGs.

10.2.3.3 Sizing

SCG patterns need to be graded to fit the range of body sizes of the target population. Adequate sizing systems are required to control fit across different bodies in the target population and through this ensure consistent pressure application across different sizes. However existing systems are often not suitable to achieve controlled pressure application, as they do not consider limb circumferences and in many cases of compression tights do not consider any circumference measurements, which are necessary to design pressure profiles across limbs. Further research is needed to identify suitable sizing systems for

SCGs. It is clear that the assumption that conventional garment or hosiery size charts can simply be applied for SCGs is mistaken.

10.2.3.4 Directions for the Technical Design of SCGs

General:

- Garment type and coverage need to be selected based on sporting activity, environment and desired effect.
- Garment form and style need to match aesthetic and expressive user needs.

Pressure profile design:

- Pressure profiles and levels need to be matched to the desired effect, sporting activity and wear situation.
- As pressures tend to vary between static and dynamic postures, a tolerated range of pressures suitable for static and dynamic postures needs to be defined.
- Pressure levels need to be checked in vivo as pressure levels measured on mannequins can substantially vary from pressures measured on human bodies.
- There needs to be a standardised methodology for the assessment of pressure application and profiles of SCGs to ensure accuracy of measurements and comparability.
- It is advisable to measure pressure in sport-specific postures to understand pressure behaviour during exercise.
- Fabric tension, desired level of pressure and circumference/radius of curvature of the limb can be used to calculate the reduction factor required for pattern development. Reduction factors can be useful as a guide, but limitations need to be considered.

Desirable fabric characteristics:

- It is advisable to select fabrics with elastic properties that do not result in large variations in load values when stretched within the likely use range (i.e. a relatively flat load-extension curve).
- Fibre composition: Elastane (>15%), nylon (or polyester)

- Fabric construction: warp knit structure; consider using varying structures or adjusting grain lines for different body parts with different demands for elasticity and pressure levels.
- Key properties:
  - Excellent wicking of moisture away from the body,
  - Excellent elastic recovery,
  - Excellent next-to-skin feel,
  - Controlled elasticity, stiffness and hysteresis,
  - Adequate thermal properties for use situation,
  - Biocompatibility,
  - Good strength and abrasion resistance,
  - Colourfastness to sweat and washing,
  - Low pilling tendency,
  - Anti-static behaviour.

Pattern design:

- Patterns need to be based on body measurements of the target population and potential variations in body dimensions and shapes based on the sporting activity need to be considered. If possible, 3D body scanning technology should be utilised to extract a large number of body dimensions. Landmarks need to be clearly defined and measurements need to be based on landmarks.
- Garment dimensions are obtained by reducing body dimensions with the calculated reduction factor. Garment patterns need to be adjusted when using different fabrics with varying elastic properties.
- Designing garment panels in 3D based on body shapes and flattening them to 2D could be useful when designing garment panels based on muscle groups.
- When designing garment panels, seam placement needs to be appraised. Based on an analysis of body movements of the specific sport, lines of non-extension can be determined.
- Different garment panels and potentially fabric structures can be used to map areas of the body that require targeted function (e.g. compression, mobility, thermal support).

- Fabric panel orientation needs to be considered carefully due to fabric anisotropy.
- Design for mobility: The garment must not interfere, impede or restrict the body movement relative to the end use, sport activity and range of movement expected. Use trials should be conducted to ensure kinetic comfort. If a specific sport posture is required, garments need to be contoured for this position (e.g. cycling position)

Sizing:

- Sizing needs to be developed in a way that the largest number of people will experience the same level of applied pressure. Grading needs to result in the same ratio of fabric tension to body limb circumference at all key body locations for every size category.
- The inclusion of limb circumference measurements as key dimensions for size charts could result in less inter-individual pressure variations.
- New sizing approaches could also consider somatotypes and different garment length options.

Garment construction:

- Flatlock seams are a must to avoid chafing and skin irritations. Seams need to be elastic to avoid breakage. Cover stitches ISO 605 and ISO 607 are good options for elastic, but strong seams.
- Non-stitch joining methods, such as adhesive bonding, for cuffs, hems and waistbands could improve comfort and pressure application, but only if elastic recovery is ensured. Hems could also be laser cut to avoid seams.

10.3 Conceptual Principles for the Design of Sports Compression Garments

As a first step in developing a framework for the design of SCGs, this section defines Design Principles for SCGs. Design principles are defined as “core principles and concepts to guide design” (Vaishnavi and Kuechler, 2015:20). These principles differ from design requirements or user needs and are understood to be conceptual, existing on a strategic level to support the design of SCGs with controlled pressure. They are general guidelines and design considerations that emerged from common themes of the findings and reflect the accumulated knowledge of this research.

1. *Know your user.*

Explore the target consumers’ functional, expressive and aesthetic needs. Understand the demands of the body, the self-identity and sporting environment. SCGs need to function consistently, i.e. apply the desired level of pressure to the wearers’ bodies, without compromising on comfort or other user needs. Allow users to focus on their sports activity without distraction.

2. *Think specific.*

SCG designs needs to be outcome-specific, target user-specific and sport-specific to provide optimal functionality.

3. *Design for the human body in motion.*

Understand the human body and its functions during exercise. Design for the ergonomics of movement.

4. *Design with intention.*

Every aspect of the garment needs to be selected for a reason and contribute to the fulfilment of user needs or the adequate provision of pressure levels.

5. *Foster confidence.*

Understand how to stimulate users’ psychological comfort and expressive needs in order to provide the wearer with a positive boost when wearing SCGs.

6. *But, always consider pressure.*

The purpose of SCGs is to apply compression. To ensure that this is achieved garments need to fit optimally on every body of the target user population. Wearer trials (WTs) and in vivo PMs are essential to achieve this since Laplace’s Law and theoretical predictions cannot be fully accurate due to variations in body surface texture and shape.

10.4 Developing a Framework for the Design of Sports Compression Garments

Considering the key findings through the three different lenses provided useful direction for the development of a design framework for SCGs, which is founded upon the conceptual Design Principles defined in the previous section. The main aim of the framework was to facilitate the design of SCGs with controlled pressure. As this research has shown, there are currently no existing processes or frameworks specifically for the design of SCGs and pressure application of commercial SCGs is not well controlled. It is necessary to have a specific framework for SCGs since the design of SCGs varies from conventional sportswear or fashion clothing. It is further essential to bring design from the "black box" method of concealed work to the "glass box" method of exposure and clarity (Jones, 1992:46–47). This is especially important for the multidisciplinary research field of SCGs to educate researchers with less garment technology knowledge about the challenges and complexity of designing SCGs and to open up opportunities for inter-disciplinary research projects with the intention to advance the design of SCGs, be it through technological developments, improved methods of predicting pressures or new ways of sizing SCGs.

This section gradually develops the design framework by utilising the three lenses again and first defining the design process (process lens), followed by a model that guides the identification of user needs (user lens) and lastly relating these needs to garment characteristics (product lens). Finally, the three elements are combined into the main model: the SCG Design Model (see Figure 10.1).

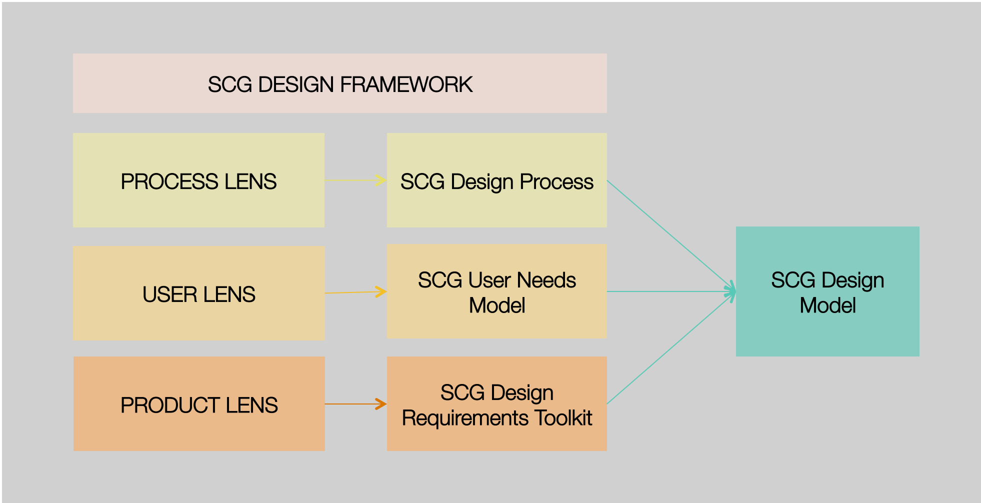


Figure 10.1: Tools of the SCG design framework emerging from the three different perspectives were combined into the SCG Design Model

10.4.1 Process Lens

As previously discussed, there are no specific, published processes for the design of SCGs, however, the principle follows the user-centred functional clothing approaches discussed in section 3.2.

10.4.1.1 Sports Compression Garment Design Process

The developed design process for SCGs is broadly based on the design process for functional clothing design defined by Watkins and Dunne (2015): 1) Research, 2) Definition, 3) Idea generation, 4) Design development and 5) Evaluation. The key process steps are presented in Figure 10.2. The process was slightly adapted to better meet the requirements of the design of SCGs. The Definition stage, which, in Watkins and Dunne's process, refers to the definition of the design problem, is understood here to be the definition of the design concept as user needs stemming from the research phase determine the SCG concept. The Idea generation stage was replaced with the design stage where all major aesthetic and technical design features are determined and the pressure profile is defined. The different stages are defined below with a more detailed presentation of the SCG Design Process in Appendix TT.

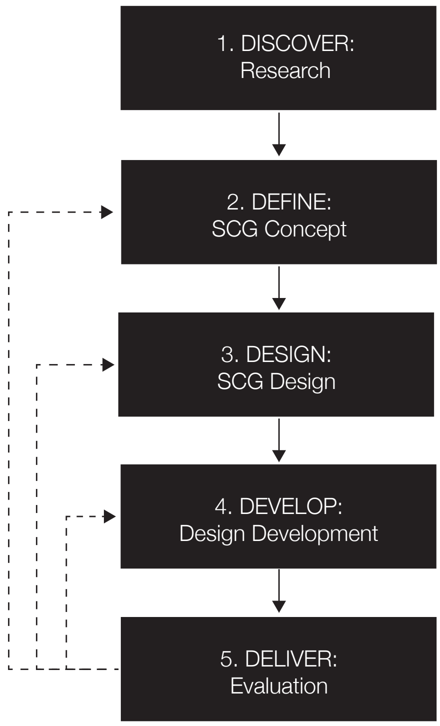


Figure 10.2: Basic stages of SCG Design Process (adapted from Watkins and Dunne, 2015)

1. Discover: Research

The design process starts with detailed research of the target user and use situation. This can be done by utilising various methods depending on the size and accessibility of the target users. Methods used for user needs identification vary depending on the market. When designing for small groups or individual elite athletes, interviews and focus groups can provide valuable insights, however, when the SCGs are designed for the mass market, online surveys can be useful to get ideas of wear behaviour, product preferences and attitudes. Observations are useful when determining body movement patterns and related mobility requirements for specific sports.

Demographic details, anthropometric data and wear behaviour (e.g. wear frequency, duration, approaches and convenience) of target users need to be researched in detail. If no existing anthropometric data set for the target population exists, 3D body scanners can be utilised to collect anthropometric data of the specific target market. Further, analysing customer reviews of existing products can give meaningful insights. Detailed analyses of the SCG market and competitor offerings help define commercial realities, including product, position, price and promotion. It is further recommended to review existing academic research in particular in regard to pressure levels and gradients. The outcome of the research stage is a list of user needs that need to be considered in the design process.

2. Define: Sports Compression Garment Concept

The Define stage determines the design concept by translating user needs into design decisions. The user needs are, thus, translated into fundamental garment characteristics. Key design decisions at this stage are related to the garment type and body coverage, pressure profile and levels as well as overall functional and aesthetic design. All these elements depend on the needs identified in the previous stage (e.g. desired effect of the SCG, sporting activity).

3. Design: Sports Compression Garment Design

In the Design stage, the design requirements evolved from the research are applied to further develop the SCG concept. Design decisions about aesthetics are made, fabrics are selected and patterns created and graded based on the pressure requirements and anthropometric data of the target users. It is a creative exploration of how to combine the listed requirements from the previous phase into SCGs. This includes decisions on garment panel shapes and fabric placement according to the specific needs of the body as well as considerations of construction methods.

The outcome of this stage is a complete aesthetic and technical design of a SCG, including technical drawings, key design specifications, garment configuration and aesthetic design. The aim in selecting the different technical garment design aspects is to design a SCG that fits well and applies the desired level of pressure to the target population across the range of sizes, whilst being comfortable.

4. Develop: Design Development

In the Design Development stage, the SCG design is developed into a prototype and the fit and PMs are assessed in order to check the accuracy of the pressure prediction. It is advisable to measure pressures in vivo on multiple individuals. The pattern can then be refined if necessary and another prototype and or a full size set should be manufactured.

5. Deliver: Evaluation

Finally, the developed SCG is evaluated against the user needs identified in the first stage before the design can enter the market. Functionality, reliability and usability are key considerations when evaluating prototypes. WTs and field tests play an essential role in assessing if functional design requirements are met by the prototype. Fit assessments, PMs and user feedback (for instance related to comfort and wear fit) can all be incorporated into WTs. Fit also needs to be assessed in dynamic poses in order to determine if the SCG acts like a second skin and moves with the body allowing freedom of movement. It is essential to use a variety of different users of the target population. Pressures applied to different users of the same size category and of different size categories need to be within the tolerated pressure range. Reliability in terms of pressure delivery and garment durability also needs to be tested. This can be done by assessing pressure after repeated wear and laundry cycles and testing the strength of seams.

Physiological tests measuring the effects of wearing SCGs during and/or after the specific sport activity that the garment is designed for can also be conducted. However, it needs to be considered that perception can play an important role in performance effects and cannot fully be controlled during physiological tests. Whilst it is assumed that the presence of pressure is essential for SCGs to have a positive effect on the wearer, the perceptual effect of SCGs is not to be underestimated. Hence, it is critical to not just assess the applied pressure in the evaluation phase, but also the usability and experience of users with the SCGs. User feedback can be gathered on the SCGs in terms of aesthetic attribute preferences, user acceptability and feelings when wearing the garments. These aspects can be assessed in questionnaires, focus groups or interviews following wear or field trials. Observations during field trials or participant diaries can further give insights into the perceptual effects of wearing SCGs.

The last step of the design process is not necessarily the final step. Depending on the outcome of the evaluation, design changes may be required. The design process is thus seen as iterative.

10.4.1.2 'Future' Technology-enhanced Sports Compression Garment Design Process

The key stage that differentiates the design of SCGs from conventional clothing is the design of the pressure profile. Designing garment patterns that apply the desired level of pressure to the wearers' bodies is the most challenging aspect of designing SCGs. Whilst the calculation of a reduction factor is a useful guide, the use of Laplace's Law on not fully cylindrical bodies comes with limitations in accuracy. Chapter 9 assessed the application of virtual fit technologies to predict pressures in order to facilitate this design stage. Unfortunately, current 3D CAD systems did not simulate technical garment properties realistically. It is hoped that future developments in cloth simulation will eliminate some of the limitations highlighted in Chapter 9 and that virtual pressure maps will simulate pressures accurately so that the technology can be integrated into the SCG design process. 3D CAD also offers the opportunity to design pattern pieces on the body avatar and then automatically flatten them to 2D pattern pieces. A future technology-enhanced design process utilising these technologies is presented in Figure 10.3. If technology was mature enough to be applied in this way, the design of SCGs with desired pressure specification would be considerably facilitated.

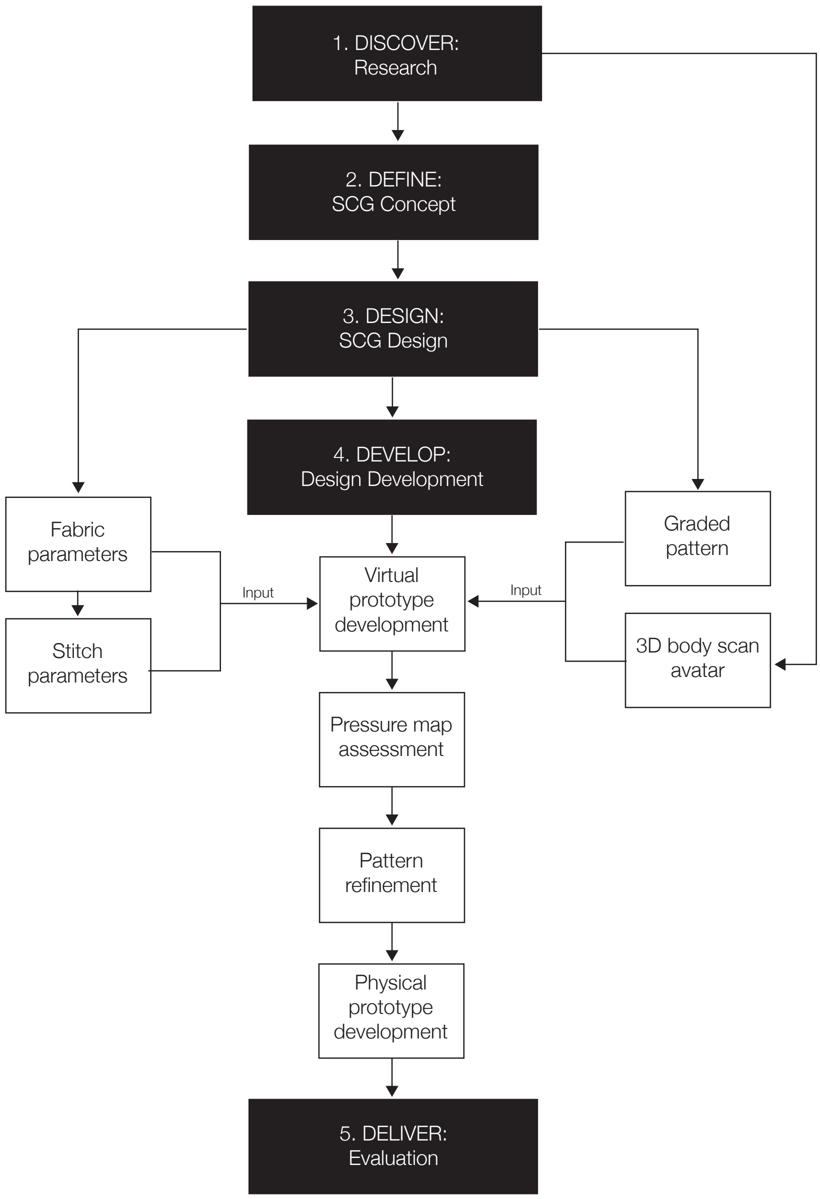


Figure 10.3: Future technology-enhanced SCG design process

The technology-enhanced process flow demonstrates that stage 4 of the design process would be vastly speeded up as initially no physical prototype is manufactured and pattern refinement can be done on the simulated garment without having to re-simulate it, making assessments of how changes to the pattern affect pressure application easy. Once the virtual prototype has been optimised, a physical prototype can be produced for the evaluation stage of the design process.

10.4.2 User Lens

When viewing the design of SCGs through the user lens, fulfilling user needs is the main concern. This includes not only users' functional needs, but also expressive and aesthetic needs (refer section 3.2.2.2). Existing research on the design of SCGs has widely neglected user needs and mainly focused on pressure quantification, however it is critical to incorporate the users' views in the context of wear behaviour, product preferences, product perception and psychological needs. In order to easily identify these needs in the context of SCGs, a SCG User Needs Model was developed. The model is loosely based on the FEA consumer needs model by Lamb and Kallal (1992).

10.4.2.1 Sports Compression Garment User Needs Model

Like the FEA model (Lamb and Kallal, 1992), the SCG User Needs Model is presented in a circular design and features the user/target consumer in the centre (see Figure 10.4). The SCG user is defined by the relationships between the body, the self-identity and the garment. 'Self-identity' is understood to be the side of the user that relates more to the expressive and aesthetic needs; the user as a being formed by experiences and the cultural environment with personal preferences as opposed to the body that acts as a carrier of the garment. Each interaction, the body/garment, self-identity/garment and body/self-identity interaction, has its own set of criteria that influences the way SCG users see, consume and perceive SCGs. Hence, these relationships need to be understood when designing SCGs. The SCG user, who is defined by the interaction of these three elements, does not exist independently, but within a specific sports environment, which shapes the user's needs in relation to SCGs through the sports activity and specific cultural characteristics.

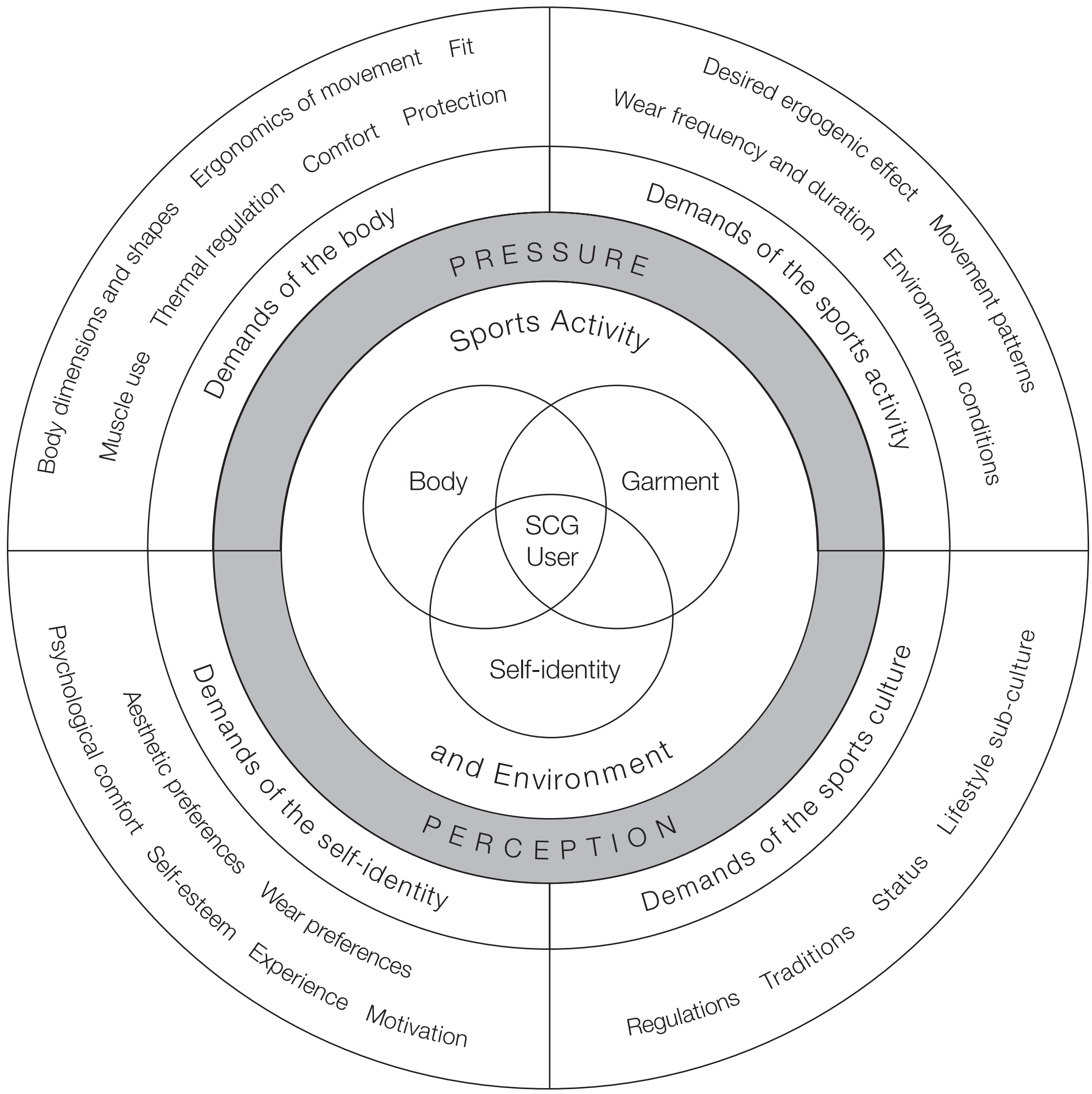


Figure 10.4: SCG User Needs Model

The body/garment-relationship plays the most important role in the functional design of SCGs and in achieving the desired pressure application. Hence, the term ‘pressure’ is highlighted in the top half of the circle, relating to the body-garment-relationship. The self-identity/garment-relationship and the self-identity/body-relationship determine perception of the garment (lower half of circle) and are related to expressive and aesthetic user needs. The self-identity/body-relationship does not directly affect garment design, but it affects the way the garment is perceived, so it can have an indirect effect on SCG design. For example, women with low body image satisfaction, which is determined by the self-identity/body-relationship, might not feel comfortable wearing whole-body SCGs. Even if the garments applied an optimal level of pressure, the SCGs might not enhance the wearers' performance due to psychological discomfort. Understanding users' psychological needs allows designers to adjust designs accordingly, such as designing a matching lightweight top or shorts with looser fit that can be worn as a second layer but does not interfere with the function of the SCGs.

It is important that the users' expectations are understood (refer Design Principle 1) and steered accordingly (refer Design Principle 5), as expectations affect perception and behaviour (e.g. placebo effect) and can help to create the desired effect (Calderin, 2011).

Pressure and perception feature in the SCG User Needs Model, as they are key elements required for SCGs to function. In line with Design Principles 5 and 6, perception and pressure need to be considered throughout the whole design process and any design decisions made need to be assessed in terms of their effect on pressure and expected effects on perception.

Rather than expressing the user needs as functional, expressive or aesthetic, the needs have been broken down into four categories that are believed to characterise the SCG user needs: demands of the body, demands of the sports activity, demands of the self-identity and demands of the sports culture. These categories are more specific and relevant for the design of SCGs. The demands of the body and sports activity are related to functional user needs, whilst demands of the self-identity and the sports culture refer to expressive and aesthetic needs. Going through each of these categories to identify specific user needs will allow the design team to find answers to the questions 'who?', 'what?', 'where?', 'when?', 'why?' and 'how?'. The four demand categories have been broken down into the key elements that need to be considered when assessing user needs. However, additional categories can always be added for specific design situations.

Demands of the Body

This category refers to all aspects related to meeting the needs of the users' bodies. It is essential for designers to understand the way the human body moves and functions during exercise (refer Design Principle 3) so that an optimal level of comfort can be achieved, which allows wearers to fully concentrate on the sports activity and perform at their best. This includes, for instance, thermal regulation behaviour and resultant body sweat patterns as well as the ergonomics of movement or potential requirements for body protection. It is crucial to investigate these aspects for the specific target consumers (refer Design Principle 2), as gender, age or discipline variations may exist. Assessing the demands of the body also involves getting access to the specific body dimensions and shapes of the target consumers.

Demands of the Sport Activity

The sports discipline and type of activity in which the SCG is going to be employed determines the effect the SCG is intended to have on the user (e.g. haemodynamic, reduction of muscle vibration, improvement of proprioception). The demands of the sport-specific body movement pattern and related key muscle groups need to be researched in detail (refer Design Principle 3). The type of sport might also determine the wear frequency and duration as well as the likely environmental conditions in which the activity is taking place (e.g. indoors or outdoors).

Demands of the Self-identity

The demands of the self-identity are very much target population-specific and can vary widely depending on the demographics and level of commitment (refer Design Principle 2). Aesthetic preferences (e.g. style, colour) and wear preferences (e.g. wear occasion, worn as base layer or outer layer) are very subjective and are likely to vary within the target population. However, it is critical to get an idea of the tendencies for the specific target group, as these preferences directly affect design decisions.

It is important to find out how psychological comfort of the target users can be met. Understanding the level of self-esteem and associated levels of body image satisfaction can give important insights into potential perceptual effects of wearing SCGs (e.g. desire for flattering design), whilst the level of experience in sport and motivation can be indicators for commitment to the sport. Users with a higher level of commitment are likely more open to advanced gear, such as SCGs to improve their performance. In accordance with Design Principle 5, incorporating these insights into garment design can foster wearer confidence.

Demands of the Sports Culture

Finally, it is important to consider the demands of the sporting culture. This includes potential regulations by sports bodies, ingrained traditions in clothing worn during the specific sports discipline as well as any desire of expressing status within the sports culture or existing trends and conventions of the related lifestyle sub-culture.

Once user needs have been assessed for each of the sub-categories, they can be summarised in a list and prioritised.

10.4.3 Product Lens

When viewing the design of SCGs through the product lens, the focus is on the technical design of SCGs and on achieving adequate pressure application, whilst fulfilling all other functional, expressive and aesthetic user needs as satisfactory as possible. To achieve this, design requirements need to be determined. This is done by translating user needs into garment characteristics. It is critical to not see the design requirements in isolation, but to understand their relationships and consider the whole garment ensemble and its interactions. A toolkit to facilitate this process is presented below.

10.4.3.1 Sports Compression Garment Design Requirements Toolkit

As per the design process described in section 10.4.1.1, it is critical to define the design concept before making more detailed design decisions. The design concept is determined by the four different aspects of user needs: demands of the body, demands of the sports activity, demands of the self-identity and demands of the sports culture. Figure 10.5 highlights the relationships between the different demands and how they influence the fundamental design decisions that define the SCG design concept.

The aspects included as fundamental design decisions are: garment type and body coverage, pressure levels and distribution, body mapping to meet localised body demands and overall garment style.

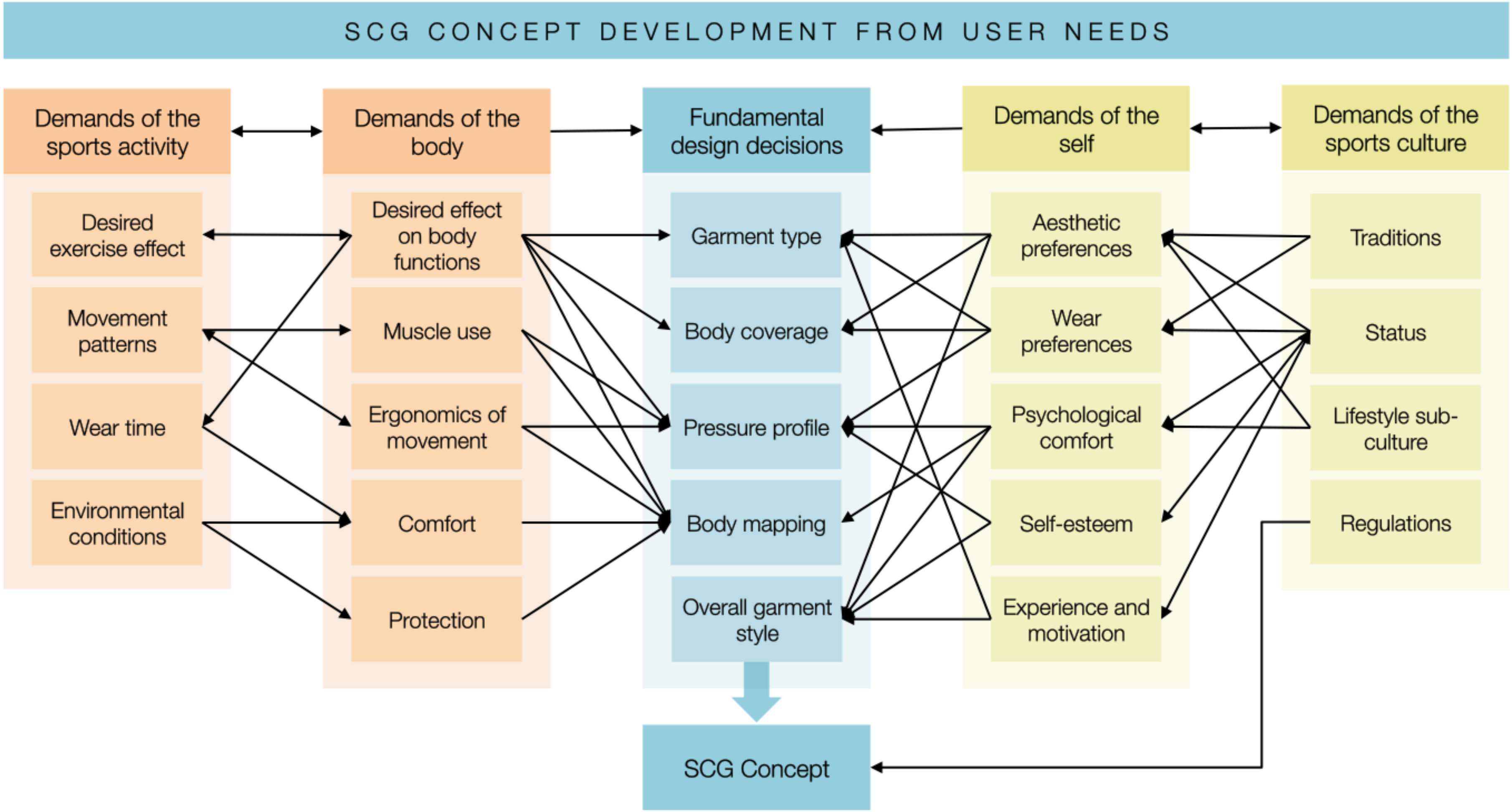


Figure 10.5: Relationships between different user needs and fundamental design decisions to define a SCG design concept

Table 10.1 lists some user needs that are regarded as universal user needs for SCGs, as they are related to the functionality of the garment. Apart from ease of care and durability, the universal user needs all directly affect the wearers' performance and, thus, must be considered by the design team when designing SCGs. Ease of care and durability were added, as sportswear requires frequent laundering and consumers expect durable products when paying a higher price for SCGs compared to conventional sportswear. These factors can also indirectly affect levels of applied pressure.

The universal user needs were translated into desired garment behaviour and design approaches that support the design team in achieving the respective garment behaviour. The design approaches were then mapped against different elements of the garment design, depicting the elements that can positively influence the desired garment behaviour. Amongst mainly technical garment design elements, the elements also include aesthetic garment design (garment form and style) and design communication. Design communication was added as a garment characteristic, as it builds part of the way the SCG is perceived by consumers. It is critical for setting users' expectations and addressing user demands. The final column in the table highlights whether there are any potential direct or indirect effects on pressure application that need to be considered when making design decisions.

It is important to not just satisfy the general functional user needs, but also those that are sports-specific and user-specific as well as expressive and aesthetic needs, which are likely to vary for different target consumers and sports environments. Table 10.2 depicts these specific user needs and provides questions that can guide the design, whilst highlighting the relation to garment design decisions and potential effects on pressure application. There is a column that allows designers to rate the importance of the different user needs on a scale of 1 to 10. Ideally, the target consumers should be involved in the prioritisation in the research phase. Prioritising user needs facilitates design decision-making, especially when there are conflicting needs.

The developed tools can help designers understand the relationship between the different user needs and garment characteristics in order to make design decisions that lead to SCGs that satisfy the users' requirements, whilst applying controlled pressure to the range of bodies in the target population.

Table 10.1: Universal user needs and associated garment behaviour mapped against potential design approaches and garment characteristics

Universal user needs	Degree of importance (1-10)	Garment behaviour	Design approaches	Garment form and style	Design communication	Fabric selection	Fabric finish	Fabric placement on body	Design of pressure profile	Pattern panel shape	Seam positioning	Size chart and grading	Construction method	Influence on pressure
Good fit	10	Garment fits like second skin	Pattern based on large number of direct body measurements.			x			x	x	x	x		+
Pressure consistency	10	Consistent pressure application across different users	Adequate sizing system and selection of target fabric elongation.			x			x			x		+
		Consistent pressure application after multiple wear occasions	Excellent elastic recovery of fabric.			x			x					+
Freedom of movement	10	Garment moves/stretches with body	Fabric with increased stretch at joints.			x		x		x	x	x	x	+
Thermal comfort	10	Adequate fabric insulation/ ventilation for use environment	Test fabric moisture management and insulation properties. Body mapped fabric placement.		x	x	x	x		x	x			(+)
		Wicking sweat away from body												
Tactile comfort	10	No discomfort or chafing.	Fabric with soft hand and potentially brushed back. Flat, strategically placed seams.			x	x						x	(+)
Easy care	8-10	Resistance to washing	Fabrics with good colourfastness and dimensional stability.			x	x							(+)

Universal user needs	Degree of importance (1-10)	Garment behaviour	Design approaches	Garment form and style	Design communication	Fabric selection	Fabric finish	Fabric placement on body	Design of pressure profile	Pattern panel shape	Seam positioning	Size chart and grading	Construction method	Influence on pressure
Durability	8-10	Resistance to pilling and abrasion.	Fabrics with good anti-pilling and – abrasion test results.			x	x							(+)
		Resistance to stresses of donning and doffing.	Fabrics with adequate tensile strength and excellent elastic recovery. Strong seam (e.g. 605, 607) and thread.			x				x	x		x	(+)

o = no likely influence on pressure application; (+) = potential indirect influence on pressure application; + = direct influence on pressure application

Table 10.2: Specific user needs and related questions to guided design mapped against garment characteristics

Specific user needs	Degree of importance (1-10)	Questions to guide design	Garment form and style	Design communication	Fabric selection	Fabric finish	Fabric placement on body	Design of pressure profile	Pattern panel shape	Seam positioning	Size chart and grading	Construction method	Influence on pressure
Ergogenic functionality		What effect is required from the SCG? Performance-enhancing, recovery-enhancing or both?		x				x					+
		What bodily function is the SCG supposed to support? Haemodynamics, muscle vibration, proprioception or other?		x				x					+
Fit		What are the body measurements of the target population?						x	x	x	x		+
		What is the main body shape of the target population?						x	x	x	x		+
		What are the key body measurements for the garment type?						x			x		+
		What sizing methodology is suitable for the target population?									x		+
Mobility		What are the predominant movement patterns of the sport activity?			x		x		x	x			+
		What are the key muscle groups involved in the movement?					x	x	x	x			+
		How do anthropometric measurements change during movement?			x		x		x	x			+
Comfort		How often and for what length is the garment likely to be worn?			x			x					+
		What are the ranges of environmental conditions in which the SCG will be worn?			x	x	x						(+)
Protection		Does the wearer require protection from the environment?			x	x	x		x				(+)
Aesthetic preferences		What are the users preferences for colour, patterns and style?	x	x	x				x			x	(+)

Specific user needs	Degree of importance (1-10)	Questions to guide design	Garment form and style	Design communication	Fabric selection	Fabric finish	Fabric placement on body	Design of pressure profile	Pattern panel shape	Seam positioning	Size chart and grading	Construction method	Influence on pressure
Wear preferences		Do users prefer to wear additional clothing over SCGs?	x	x	x	x							(+)
Psychological comfort		What garment design aspects improve psychological user comfort?	x	x	x				x				(+)
Self-esteem		What garment aspects can boost the wearers' confidence?	x	x	x								(+)
		How can the garment be designed to be flattering for the female body?	x	x			x		x	x			o
Experience		How experienced are the wearers in the sporting activity?	x	x									o
		What is the wearers' level of commitment to the sport?	x	x									o
Motivation		What is the level of motivation for the relevant sport?	x	x				x					o
Regulations		Are there any restrictions for sports clothing worn during competitions?	x		x	x		x					(+)
Traditions		Are there any traditions or unwritten laws related to the appearance of sports clothing for the particular sport?	x	x									o
Status		What is the SCG required to express about the user and his/her status as a sportsperson?	x	x									o
Lifestyle sub-culture		Is the lifestyle sub-culture of the particular sport? If so, what are the themes and trends?	x	x									o

o = no likely influence on pressure application; (+) = potential indirect influence on pressure application; + = direct influence on pressure application

10.5 The SCG Design Model

"In theory, there is no difference between theory and practice. In practice, there is." (Norman, 2013:236). The three different design tools presented in the previous section were developed for each of the three different lenses: the process lens, the user lens and the product lens. Hence, they only focused on one element of SCG design. The three different tools (the SCG Design Process, the SCG User Needs Model and the SCG Design Requirements Toolkit) were therefore combined into one main model for the design of SCGs. The SCG Design Model is more compact and streamlined and thus can be more easily applied in a practical design environment. The individual tools described in the previous section can be used as more detailed guides for the design of SCGs. The SCG Design Model is presented in Figure 10.6. It aims to facilitate the systematic design of SCGs with controlled pressure that fulfils the needs of the target consumers.

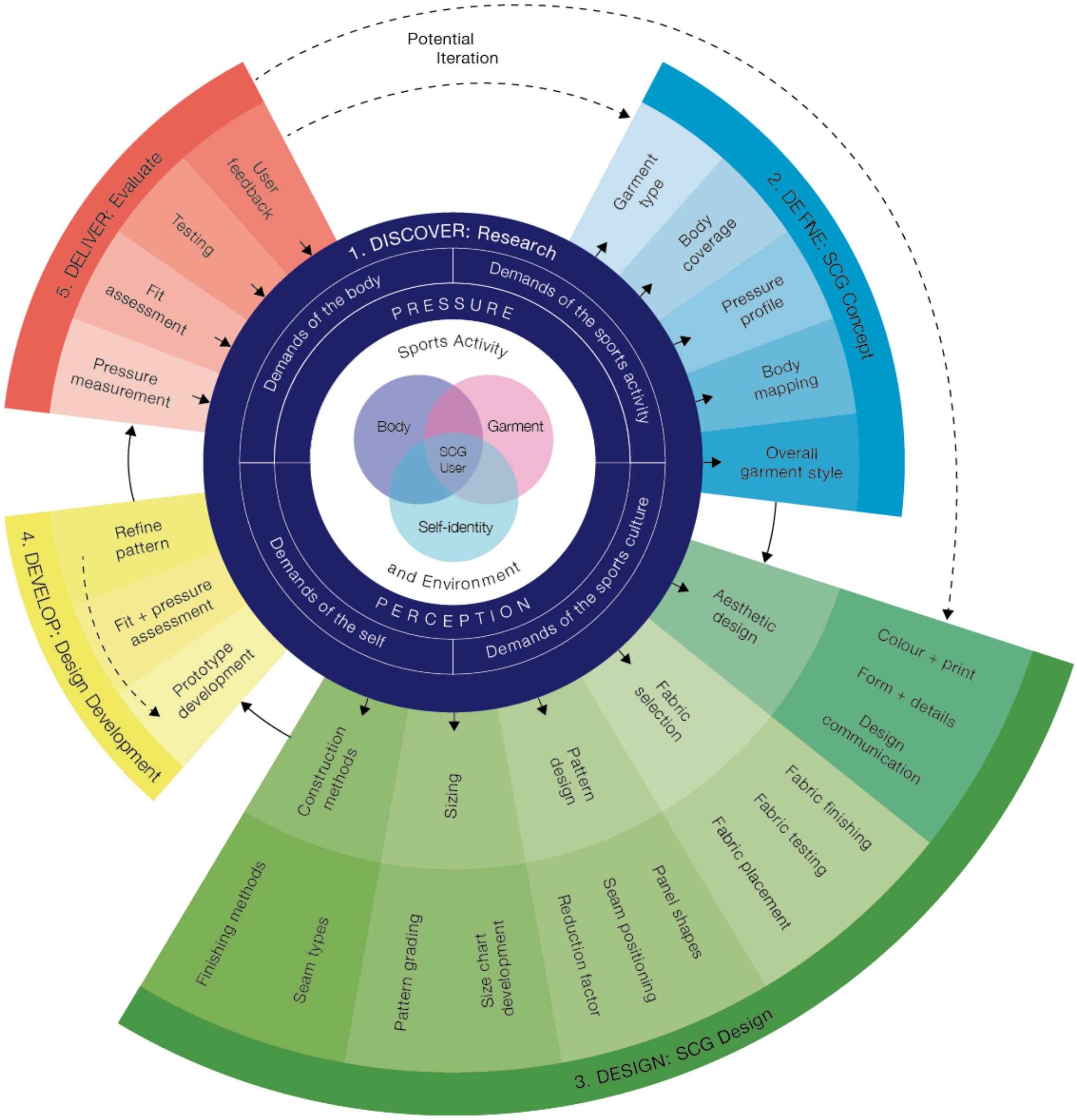


Figure 10.6: The SCG Design Model

The SCG Design Model is based on the five process stages defined in the SCG Design Process (refer section 10.4.1.1). It also features a simplified version of the SCG User Needs Model (refer section 10.4.2.1) at the centre, which represents the first process stage (Define) and informs all subsequent stages. The four succeeding stages of the SCG Design Process, Define, Design, Develop and Deliver, are arranged around the SCG User Needs Model with arrows indicating the direction of the process flow. The tools of the SCG Design Requirements Toolkit (refer section 10.4.3.1) were incorporated into stages 2 (Define) and 3 (Design) of the SCG Design Model. The fundamental design decisions identified as part of the toolkit are listed under the Define stage to guide the designer in defining the SCG concept based on user needs. The third stage makes up the largest part of the SCG Design Model, as it is the stage where more detailed decisions about the garment design are made. The main categories are broken into subcategories to guide design teams. Stage 4 is the only stage that involves potential iteration, as a prototype is developed, assessed in terms of fit and applied pressure and then refined. The final evaluation of the designed SCGs returns to the user needs defined in the first stage in order to validate the design. If the user needs are not met, the process returns to the Define or Design stage of the process, where all subsequent stages are iterated to optimise the SCG design.

The SCG Design Model is not a definitive pathway to the optimal design of SGCs. It is rather a starting point in the complex process towards the design of SCGs with controlled pressure, which has not been given much attention in current research. The model is viewed as a productive proposal on how SCG design can be improved and a guide for future research. It will likely evolve over time as technologies and knowledge progress. If the framework can “trigger new insights and development” (Östmann, 2005:8) (refer section 4.4.5), then the purpose of this research has been accomplished.

10.6 Chapter Summary

This chapter described Phase IV of this research project. Phase IV was a critical phase, as it drew together the key findings from the preceding phases. The key findings were viewed with three different lenses: the process lens, the user lens and the product lens. The synthesis of findings brought about recommendations for the operational design of SCGs followed by the development of six conceptual principles for the design of SCGs, which were the foundation for the development of a framework for SCG design. Starting with these principles, the researcher successively developed design tools for each of the three different lenses. The outcomes were a SCG Design Process, a SCG User Needs Model and a SCG Design Requirements Toolkit. These three tools were then combined into a more concise SCG Design Model that is thought to be more suitable for the practical design environment, whilst the more detailed tools are useful for more comprehensive theoretical reference.

The developed SCG Design Model and related knowledge has the potential to improve SCGs by, on the one hand, enhancing the theoretical knowledge base, which is expected to lead to more holistic and better-informed research on SCGs and, on the other hand, facilitating the design of SCGs with controlled pressure in practice. As such, the developed model has the potential to benefit SCG researchers, SCG design teams and SCG consumers.

This chapter highlighted the complexity of designing SCGs in terms of identifying and fulfilling user needs, but also in designing the technical garment aspects. Achieving controlled pressure is a complex task and due to lack of existing technology that can realistically simulate garments on a body avatar, the process has to rely on traditional pressure calculations derived from Laplace’s Law. Further research is needed to develop an appropriate sizing methodology for SCGs, an area that has been neglected by existing research. In addition, this chapter highlighted that the perceptual effects of wearing SCGs are critical and need to be understood and addressed by the design team. Understanding users’ aesthetic concerns and respecting their cultural sports environment is important in addition to understanding the functional requirements of the human body and sporting activity.

11 SUMMARY CONCLUSIONS AND RECOMMENDATIONS

11.1 Introduction

Despite a wealth of research on the functionality of sports compression garments (SCGs) that emerged due to their increased popularity among elite and recreational athletes and brands' claims that they improve exercise performance and shorten recovery, garment characteristics have been neglected. This is linked to the background of researchers investigating SCGs being mainly in the medical or sports science fields. Systematic research considering the complex interactions between applied pressure and the wearers' body measurements, garment construction, fabric properties and the size of the garments was lacking. Further, SCG users and their needs and attitudes had not received any attention.

There was no previous research identifying the factors critical to the design development of SCGs. As a consequence, no theoretical framework for the design development of SCGs existed, resulting in inconsistent pressures applied by SCGs. Hence, there was a need for research that creates a better understanding of the SCG-body-relationship in order to identify ways to design SCGs with controlled pressure.

This study set out to enhance theoretical and practical knowledge on the design of SCGs to define a framework for the design of SCGs with controlled pressure. The study sought to analyse the existing research base of SCGs (Phase I) as well as analyse commercial SCGs and explore users' experiences with them (Phase II) in order to create an improved understanding of the SCG-body-relationship. The study further sought to evaluate the use of virtual fit technology to facilitate the design of SCGs (Phase III) and eventually develop design principles and guidance for the design of SCGs for the benefit of SCG scholars and designers (Phase IV).

11.2 Summary of Empirical Findings

11.2.1 Aim 1

Aim 1 of this research was to analyse the existing knowledge base related to SCGs with specific focus on applied pressure. It was fulfilled by a comprehensive review of existing literature on SCGs in the context of sport (Chapter 2) and a review of literature related to the design of SCGs (Chapter 3).

The critical analysis of the wealth of studies investigating the functionality of SCGs highlighted the ambiguity in the research field of SCGs, which inhibits reliable judgements about the functionality of SCGs. A shift in thinking towards a more holistic approach considering the interrelations of the body and its movement and SCGs with all their complex properties and applied pressures is required.

It was found that the existing research base is lacking quantifiable measurements and guidelines that can be useful for the technical design of SCGs, hence Chapter 3 related literature from more generic fields to the context of SCGs.

The ability to design SCGs with controlled pressure profiles appears to have been underestimated by researchers, whilst the effects of SCGs appear to be overemphasised by SCG brands that selectively choose research studies to ‘prove’ the benefits of their products. The research field of SCGs was conceptualised in an overview map and knowledge gaps in relation to the design of SCGs were summarised (Chapter 5) and form the outcome of Aim 1.

11.2.2 Aim 2

Aim 2 was to identify SCG users’ wear behaviour, their product preferences and attitudes towards SCGs. It was achieved through an online survey that evaluated user experiences with SCGs (Phase II – Study 1). The conclusions from the online survey found that there was a high level of satisfaction with commercial SCGs. Differences in the use of SCGs existed based on beliefs in the functionality of SCGs and gender. SCGs for female athletes need to be aesthetically pleasing in style, as female respondents were not just concerned about product price and fit, but also their appearance and tended to wear SCGs as outer layer. The survey further indicated that the feeling of wearing SCGs can be positively or negatively influenced by levels of body image satisfaction, which could impact on a potential placebo effect of SCGs.

11.2.3 Aim 3

Aim 3 was to analyse commercial women’s SCGs with a particular focus on garment design, materials used, sizing systems applied and pressures elicited. It was fulfilled by the garment and fabric analyses of Skins A400 Women's Long Compression Tights and Long Sleeve Top as well as a review of size charts of commercial SCGs (Phase II – Study 2).

The analyses of commercial SCGs provided insights into key fabric properties, pattern design and garment construction techniques used for SCGs. It highlighted the importance of fabric properties for the design of SCGs. The design of SCGs varies from conventional sportswear design, as the ultimate goal of the design is the application of specific pressure levels at certain locations across the body. To achieve this, fabric properties, fit and sizing are crucial. It is essential to use high-quality fabrics with excellent elastic recovery and analyse anthropometric data of the target population for optimal fit. There is a need for improved size charts that consider girth measurements due to the interrelation of fabric tension and limb girth in pressure delivery (Laplace's Law).

11.2.4 Aim 4

Aim 4 was to create an improved understanding of how pressures applied by SCGs behave in relation to body dimensions and shapes. It was accomplished through wearer trials (WTs) with SCGs (Phase II – Study 3). It was found that the pressure application of the commercial women's SCGs under investigation was not well controlled and it was questioned whether the pressure levels were sufficient and distributed adequately to have any physiological effects on the wearer to improve exercise performance or recovery. Variations in pressure levels were likely caused by variations in fit due to problems with the applied sizing system.

The WTs further revealed that wearers' perceptions of compression and fit levels are not necessarily related to in vivo pressure levels, but rather their own subjective perceptions, which can be influenced by personal preferences, body cathexis and self esteem.

11.2.5 Aim 5

Aim 5 was to evaluate the use of virtual fit technologies to predict pressures applied by SCGs. It was fulfilled with the evaluation of the three-dimensional (3D) computer-aided design (CAD) programme Optitex PDS 11 as a tool for pressure prediction in the design of SCGs (Phase III, Chapter 6). Findings highlighted problems with the accurate simulation of technical garment properties, despite advances in simulation technologies. Problems with reliability, limitations of built-in parametric model morphing and the ambiguity of fabric and stitch parameter settings were highlighted. It was concluded that 3D CAD virtual fit technologies are currently limited to the visual representation of garments for marketing and sales purposes, but are not useful for technical product development or pressure prediction.

Rather than focusing on the realistic visualisation of garments with positive ease, future developments of commercial clothing-specific 3D CAD software should be based on collaborations between textile and garment technologists as well as computer scientists to develop 3D CAD programmes that realistically simulate garments on body avatars for technical garment evaluation.

11.2.6 Aim 6

Lastly, Aim 6 was to define a design framework that improves the ability to design SCGs to pre-determined pressure specifications. It was realised through the synthesis of findings from Aims 1 to 5, which led to the definition of six conceptual Design Principles for SCGs. They formed the foundation for the development of a framework for the design of SCGs (Phase IV). The framework was successively developed utilising three different lenses: the process lens, user lens and product lens. The outcomes were the SCG Design Process, the SCG User Needs Model and the SCG Design Requirements Toolkit, which were combined into a more concise model that combines the three perspectives: the SCG Design Model with the purpose of facilitating the design of SCGs with controlled pressure.

11.3 Contributions to Knowledge

11.3.1 Originality

The study applied an original methodological framework rooted in a pragmatist research philosophy and informed by the concepts of Interdisciplinarity, Pasteur's Quadrant and Design Science Research. It applied an inductive approach, which allowed the study to develop into an unanticipated outcome based on the findings of the empirical research. This was a novel approach in the field of SCG research, which has previously mainly been based on deductive experiments. The broader, interdisciplinary approach of this research enabled knowledge to emerge that would not have emerged otherwise. With no research focusing on SCG users, it was not clear at the outset of the study that self-identity and perceptual effects would play such an important role in the design of SCGs. This knowledge emerged from the empirical findings of this research and gradually created the knowledge that led to the final SCG Design Model.

So far, researchers have approached the research topic of SCGs from the viewpoint of a single discipline. This study showed that single-disciplinary views are biased, but that evaluation and synthesis of different views can lead to a more comprehensive, less biased understanding of SCGs and their design requirements. Interdisciplinarity is seen as an applied orientation that builds bridges between the different disciplines related to SCGs. This study was the first study to analyse the various relevant disciplinary perspectives and integrate their insights to produce a more comprehensive understanding of SCGs.

Whilst applying a more holistic research approach, the main focus lay on the technical garment design, an area with only very limited existing research. Prior to this research, no study had examined the product development, fit and sizing of SCGs. A novel fit assessment method was developed specifically for the use of SCGs as fit evaluation of SCGs varies substantially compared to garments with positive ease. By conducting an online survey with SCG users and WTs, this study was also the first to explore user perceptions and needs related to garment attributes and attitudes towards SCGs.

Finally, the tools within the SCG Design Framework and the SCG Design Model are original tools that can support the design of SCGs. No comparable models or tools have previously existed to guide researchers and designers in the field of SCGs.

11.3.2 Contribution to Theory

The study significantly contributed to the theoretical knowledge base of SCGs. Figure 11.1 highlights the knowledge gaps identified in Chapter 5 and maps the areas that were addressed by this study. This visual map demonstrates the theoretical contribution made by this research. It visualises that the contributions to theory of this study lay on the clothing design, technologies, textiles and design process categories. The research also opened up new research areas related to SCGs: clothing psychology and body image, owing to the inductive methodological approach of the study. Figure 11.1 also serves as a tool to identify areas of ambiguity and lack of research. These areas are mainly related to compression, in particular the level of pressure required, pressure profiles and pressure prediction, which will have to be addressed by future research.

Figure 11.1: Overall areas of research related to SCGs and knowledge gaps addressed by this study

An addition to the theoretical research base developing from this study is the distinction between the wearer and relevant functional needs and self-identity within the context of SCGs. Previously, SCGs have only been viewed from a functional perspective. However, even the view from a functional perspective was narrow and has been broadened by this study to include fit and comfort aspects and related technical design elements. This study, thus, introduced a new perspective to the research field of SCGs by considering the design of SCGs and its effect on compression and users. Table 11.1 summarises how the study addressed the specific knowledge gaps related to the design of SCGs that were identified in Chapter 5.

Table 11.1: How this study has addressed gaps in the research field of SCGs

Identified research gap	New knowledge emerging from this study addressing the gap in research
No consideration of users' perception and psychology of wearing SCGs	An online survey and wearer trial questionnaire provided insights into users' opinions and attitudes towards SCGs, highlighting that levels of body image satisfaction can influence a potential placebo effect of wearing SCGs.
No practical models for pressure prediction	The use of 3D CAD virtual fit pressure maps for pressure prediction was evaluated, however, technology is currently not mature enough to simulate compression realistically. The developed SCG Design Model provides a framework for the whole design development of SCGs incorporating traditional methods to predict pressures based on Laplace's Law.
No optimal pressure level	The determination of optimal pressure levels for ergogenic effects of SCGs exceeded the scope of this study. However, the analysis of existing literature showed that positive and no effects were reported by studies for a variety of different pressure levels.
Effects of movement on pressure not understood	The study quantified variations in pressure levels in different body postures and found that pressures were significantly influenced due to variations in fabric tension and/or limb circumferences.
No research on how to design SCGs for optimal comfort	The study assessed subjective comfort levels of wearer trial participants and related them to garment design. Technical garment design characteristics that can enhance comfort were identified in the review of design-related literature. These include pattern design for optimal fit, sizing, seam placement, and fabric selection and placement.
No guidance on how to design SGCs to user needs	The study developed a SCG User Needs Model and a comprehensive toolkit on how to translate these needs into design requirements.
No studies on grading and sizing of SCGs	The literature review provided an overview of how to implement grading and sizing for stretch garments with negative ease. The study further identified grading and sizing techniques used by SCG brands highlighting the need for more adequate sizing systems that are designed purposely for SCGs.

Identified research gap	New knowledge emerging from this study addressing the gap in research
No studies on manufacturing techniques for SCGs	The study identified manufacturing techniques used for performance sportswear in the literature review and in the review of the commercial SCGs under investigation. Flat seams are essential to improve comfort and minimise effects on pressure levels.
No research on SCG design processes	The study defined a SCG Design Process. It further proposed a future technology-enhanced design process, which could be realised with improved 3D simulation technologies.

The contributions to theoretical knowledge made by this study have the potential to improve SCGs by leading to more holistic and better-informed research on SCGs.

The theoretical contributions of the developed conceptual Design Principles and range of design tools (SCG User Needs Model, SCG Design Requirements Toolkit) could go beyond the field of SCG research, as many of the concepts and principles are relevant to design research in the context of functional clothing (e.g. protective clothing, clothing for specific needs, medical clothing).

Table 11.2 gives an overview of the specific contributions to theory of the individual research aims.

Table 11.2: Contribution to theory of the individual research aims

Research Aims	Contribution to Theory
1. To analyse the existing knowledge base related to SCGs with specific focus on applied pressure.	The output of Aim 1 was an overview map of the research field of SCGs, highlighting the multidisciplinary nature of the topic and the need to cross-fertilise knowledge between disciplines. It has further outlined research gaps in the field. This knowledge is a valuable contribution to guide future research on SCGs.
2. To identify users' wear behaviour, preferences and attitudes related to SCGs.	Aim 2 has provided insights into the untouched field of use experiences and user perceptions in relation to SCGs. This new knowledge broadened the current research field by revealing that not just functional needs, but also the feeling when wearing SCGs and aesthetics are key to the effectiveness of SCGs. This provides a new perspective to the research field.
3. To analyse commercial women's SCGs with particular focus on design, materials, sizing and applied pressure.	Aim 3 contributed to the theory of SCG design by providing exemplary values of fabric and garment properties of SCGs, which future research can use as a point of comparison. It further highlighted problems with sizing of SCGs and the need for more research in this area.
4. To create an improved understanding of how pressures applied by SCGs behave in relation to body dimensions and shapes of female recreational athletes.	By identifying problems with fit and applied pressure of commercial SCGs, Aim 4 created an appreciation of the complexity of pressure application. Researchers from the medical and sports science fields, who have currently neglected garment characteristics, will be able to appreciate the importance of garment characteristics in relation to pressure delivery.

Research Aims	Contribution to Theory
5. To evaluate the use of 3D CAD virtual fit technology as a tool to predict applied pressures in the design process of SCGs.	Aim 5 added to the existing knowledge of limitations of current 3D CAD programmes by evaluating more detailed parameter settings than previous research and by attempting to circumvent these limitations. It provided new insights into the shortcomings of current technologies, which will be useful for researchers attempting to employ virtual fit technologies.
6. To define a design framework that improves the ability to design SCGs to pre-determined pressure specifications.	Aim 6 developed conceptual Design Principles to guide the design of SCGs as well as the SCG Design Model. They represent the first design framework for SCGs and thus offer a valuable contribution to theory. Future research can apply the SCG Design Model or further build on it.

11.3.3 Contribution to Practice

In line with the pragmatist research philosophy of this study, contributions to practice are as important as contributions to theory. The developed SCG Design Model is underpinned by theoretical findings but practicable in the apparel industry. The developed model and associated new knowledge emerging from this study have important practical implications for the design environment of SCG brands. They allow brands to apply a systematic user-centred approach to designing SCGs, which is likely to result in a more efficient design process with fewer design changes late in the product development phase. The research has the potential to improve the functionality of SCGs and allows brands to better understand users and their needs. Through this, SCG brands can clearly communicate product specifications and address design communication to meet users' needs, allowing customers to make informed purchase decisions. Therefore, both SCG brands and consumers can benefit from the outcome of this research.

Industry professionals from other sportswear sectors may also gain design insights from this research and the developed SCG Design Model. There is potential to apply the model in the design development of other tight-fitting apparel products or in the design of medical compression devices.

Table 11.3 provides an overview of the specific contributions to practice of the individual research aims.

Table 11.3: Contribution to practice of the individual research aims

Research Aims	Contribution to Practice
1. To analyse the existing knowledge base related to SCGs with specific focus on applied pressure.	As there is currently very limited research on the design of SCGs, Aim 1 collated all knowledge relevant to the design of SCGs by linking existing clothing and textile research to SCGs. The comprehensive knowledge base created by this study will be of great value to design teams.
2. To identify users' wear behaviour, preferences and attitudes related to SCGs.	By being the first study to identify the importance of users' expressive and aesthetic needs in relation to the functionality of SCGs, Aim 2 has contributed valuable insights for SCG brands, which can incorporate this knowledge into their design considerations and design communication.
3. To analyse commercial women's SCGs with particular focus on design, materials, sizing and applied pressure.	Aim 3 highlighted problems with existing commercial SCGs. It is hoped that by identifying these problems brands will put more effort into developing more effective SCGs, especially in terms of sizing and pressure application.
4. To create an improved understanding of how pressures applied by SCGs behave in relation to body dimensions and shapes of female recreational athletes.	The findings from Aim 4 have led to a comprehensive list of directions for the technical design of SCGs, which will be valuable to design teams on an operational level, as there is currently no guidance for the practical design of SCGs.
5. To evaluate the use of 3D CAD virtual fit technology as a tool to predict applied pressures in the design process of SCGs.	The outcome of Aim 5 was a list of recommendations for future developments in 3D CAD that emerged from this study. These recommendations have the potential to improve clothing-specific 3D CAD programmes and to start a dialogue between commercial software developers and textile and clothing technologists.
6. To define a design framework that improves the ability to design SCGs to pre-determined pressure specifications.	The output of Aim 6 was the SCG Design Model, which makes an important contribution to the practical design environment of SCGs by incorporating the theoretical knowledge developed in this research and turning it into an easy-to-apply model. It hence can improve future SCGs.

11.4 Limitations

The analysis of SCG users' views, commercial SCGs and their behaviour on various human bodies as well as the evaluation of virtual fit for pressure prediction encountered a number of limitations, which have been outlined in detail in Chapter 4.

The use of a non-random sampling techniques for the online survey and WTs were potential limitations, yet appropriate for the context of this study, as no sampling frames of SCG users exist. The sample sizes of the online survey (N = 200) and wearer trials (N = 33) were big enough to derive conclusions and apply statistical tests, but findings are not generalisable to the whole population of SCG users.

The analysis of commercial SCGs was based on Skins A400 Women's Long Sleeve Compression Top and Long Compression Tights with comparisons being made to other SCG fabrics and garments (SUB Sport) for the fabric analysis and pressure measurements (PMs) on mannequins, respectively. Hence, the properties obtained from the fabric and garment analyses are only valid for the specific SCGs used for the analyses.

It further needs to be considered that judgements about the use of virtual fit as a tool for pressure prediction are only valid for the 3D CAD programme (Optitex PDS 11) and simulation settings used in this study. However, even more shortcomings in the virtual fit process were encountered when attempting to use other 3D CAD programmes (VStitcher and Gerber 3D) at the outset of Phase III of this research.

Based on the methodological framework and pragmatist research philosophy, the study set out to structure thinking and provide "provisional truths" (Johnson and Onwuegbuzie, 2004:18) (refer section 4.2.1) about the design of SCGs and offer a productive proposal on how the research and practice related to the design of SCGs could be improved. As a direct consequence of the methodological approach, generalisability of empirical findings was not the focus of this research, but rather the creation of new knowledge within a specific context, which has been achieved as outlined in the previous sections.

11.5 Recommendations for Further Research

The limitations outlined in the previous section should be addressed by further research. Study 2 of this research could be further developed by analysing a range of different commercial SCGs from different brands and comparing the garment and fabric properties and their effects on compression. Similarly, Study 3 could be further developed. WTs with additional garments would allow for comparisons of pressure levels and distributions across different garments and could provide valuable insights into users' design preferences. The suitability of different sizing systems could also be evaluated through fit assessments. Larger sample sizes within each size category could lead to clearer insights about the correlation between body dimensions and pressure distribution. It would be worthwhile to further examine the effects of movement on pressure application. Future developments of PM devices enabling the measurement of dynamic pressure during exercise could aid the research.

Whilst the new knowledge emerging from this research provides a substantial contribution to the research area of SCG design, the research area is still in its infancy. A natural next step would be the application of the SCG Design Model in the practical design of a specific SCG.

In order to make more informed fabric selection decisions, more research is required to understand how specific fabric characteristics, such as fibre, yarn and construction properties, affect the application of compression pressures by garments.

This study has touched on the effects of wear and care of SCGs on pressure levels. Studies assessing pressure delivery over long-term use and repeated laundering of commercial SCGs could give further insights into potential pressure losses over time.

An area of research with a large influence on SCG performance across individuals is sizing of SCGs. Further research is needed to develop an appropriate sizing methodology for SCGs. The inclusion of limb circumferences in SCG sizing systems could be beneficial for compression sportswear due to the link between pressure and limb circumferences (Laplace's Law).

The research opened up a new area in the field of SCG research: the psychology of wearing SCGs. This area has subsequently been neglected, yet it seems to play a critical role in the application of SCGs as ergogenic aids. A wide range of research opportunities arise within this context. Some aspects directly arising from this study are listed below:

- The relationship between women's body image satisfaction and psychological comfort of wearing SCGs,
- The relationship between women's body image satisfaction and expressive and aesthetic needs for SCGs,
- Perceptions of overheating related to body coverage,
- Ways in which product communication and/or design aspects can enhance psychological comfort.

The SCG Design Model facilitates the design of SCGs to given specifications, but does not advise designers what specifications (e.g. level of pressure) result in optimal exercise performance or recovery. These specifications will have to be determined by further research, which should ideally be collaborations between garment and textile technologists and sports scientists. Such multidisciplinary research could result in improved SCGs. The following recommendations for future research on the functionality of SCGs emerged from this study:

Effects of SCGs:

- More studies with the same, improved study design and garments and larger, homogenous sample sizes are required.
- A more standardised approach to the performance testing of SCGs with clear study designs is needed including a more detailed focus on the intervention, i.e. the SCG used and its properties and applied pressures.
- SCGs and participants should be described in detail.
- Studies should give more consideration to perceptual effects of SCGs and consider participants' attitudes and opinions towards SCGs.
- Methods accounting for placebo effects should be developed by considering subjects' beliefs in the performance- and recovery-enhancing properties of SCGs and/or by influencing these beliefs.
- To find out which sporting activities benefit from compression treatment and which levels of body coverage, pressure and wear times are most beneficial, the same participants should be tested under these different conditions.
- A long-term study is required to investigate the effects of SCGs on injury prevention.

Evaluation of SCGs:

- There is a need for a framework for the systematic evaluation of the overall performance of SCGs for a meaningful comparison of different SCGs.

11.6 Implications for Research and Industry

The design of SCGs is complex and not all relationships between garment characteristics, the wearer's body and applied pressure are currently understood.

Achieving controlled pressure is an elaborate task and, due to lack of existing technology that can realistically simulate garments on a body avatar, the process has to rely on traditional pressure calculations derived from Laplace's Law. However, user satisfaction and the belief in the functionality of SCGs is not necessarily related to exact PMs but is more related to personal preferences and body satisfaction. Hence, perceptual effects of wearing SCGs are critical and need to be understood and addressed by the design team. Understanding users' aesthetic concerns and respecting their cultural sports environment is important in addition to understanding the functional requirements of the human body and sporting activity.

At the outset of this study, the majority of SCG research focused on measuring the functionality of SCGs with some related research in the medical field mainly focusing on PMs of compression bandages or garments. By applying an inductive interdisciplinary methodological approach, this work has provided a different perspective to the research of SCGs. This approach has created new knowledge and tools for the design of SCGs and opened up new areas of research, which is hoped to initiate discourse in the field.

The developed SCG Design Model has the potential to improve SCGs by, on the one hand, enhancing the theoretical knowledge base, which is expected to lead to more holistic and better-informed research on SCGs and, on the other hand, facilitating the design of SCGs with controlled pressure in practice. As such, this work has the potential to benefit SCG researchers, SCG design teams and SCG consumers. Thus, it made a vital contribution towards the design of SCGs with controlled pressure.

The design of effective SCGs could further improve athletes' lives as the SCGs have the potential to improve performance, shorten recovery and prevent injuries, which would have wider positive economic implications, such as reduced healthcare costs.

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APPENDICES

Appendix A. The human body and sport

Energy Systems

Every movement made by the body is triggered by the contraction of muscles. The primary source of energy for muscle contraction is the high-energy compound Adenosine Triphosphate (ATP), stored inside muscles. ATP releases its energy when converted into Adenosine Diphosphate (ADP) by removing phosphate (Guyton and Hall, 2006; McConnell and Hull, 2011; Draper and Marshall, 2013). However, the amount of ATP present in muscles is only sufficient for the first three seconds of muscle contraction (Guyton and Hall, 2006; McConnell and Hull, 2011; Marieb, 2012). As ATP is the only energy source that can fuel muscles directly, it needs to be resynthesised immediately by restoring the missing phosphate molecule on ADP to keep the muscles working (MacLaren and Morton, 2012; Marieb, 2012). Three different metabolic pathways can achieve this: the phosphagen system (ATP-PCr pathway), glycolysis and the aerobic system (Guyton and Hall, 2006; Phillips, 2015). Both the phosphagen system and glycolisis are anaerobic systems (Draper and Marshall, 2013). Which system is used to synthesise ATP depends on the amount of ATP required, consequently the intensity and duration of exercise.

The Phosphocreatine system is based on the direct phosphorylation of ADP by creatine phosphate (Marieb, 2012). It can, thus, synthesis ATP much faster than the other two systems. However, the supply of creatine phosphate in the muscle is also limited. It is only sufficient to provide energy for short bursts of maximal muscle power, such as 100-metre sprints (Guyton and Hall, 2006).

Glycolysis requires ten reactions to produce ATP and pyruvate (Draper and Marshall, 2013). During intense muscle activity, when oxygen supply is insufficient, pyruvic acid is transformed into lactic acid, which enters the blood flow (Guyton and Hall, 2006; Marieb, 2012). Because glycolysis represents a relatively fast production of considerable amounts of ATP, it is good for short to moderate periods of muscle contraction, such as 200- to 800-metre runs (Guyton and Hall, 2006).

The aerobic pathway is the only system that cannot only catabolise carbohydrates, but also fats and proteins to synthesise ATP. Each macronutrient uses its specific pathway through which it is initially catabolised, prior to entry into the common pathways of the Krebs cycle and the electron transport chain (Draper and Marshall, 2013). It is a complex system, which is slow and requires a constant supply of oxygen and nutrients (Marieb, 2012); however, it produces a large amount of ATP (Draper and Marshall, 2013). It is, thus, required for endurance exercise, such as marathon runs (Guyton and Hall, 2006).

In general, most exercise protocols utilise energy originated from both aerobic and anaerobic systems, however the level of contribution differs (Jones and Barker, 1996). Exercise beyond 60 seconds requires mainly aerobic energy sources (MacLaren and Morton, 2012). Appendix Table A-1 gives an overview of the various energy sources used for different sports activities.

Appendix Table A-1: Overview of metabolic systems and related exercise types (Adapted from Guyton and Hall, 2006)

Metabolic system	Examples of exercise utilising system
Phosphagen system	100-meter dash, jumping weight lifting, diving, Football dashes
Phosphagen and anaerobic system	200-meter dash, basketball, baseball home run, ice hockey dashes
Anaerobic system	400-meter dash, 100-meter swim, tennis, soccer
Anaerobic system and aerobic system	800-meter dash, 200-meter swim, 1500-meter skating, boxing, 2000-meter rowing, 1500-meter run, 1-mile run, 400-meter swim
Aerobic system	10,000-meter skating, cross-country skiing, marathon run (26.2 miles, 42.2 km), jogging

Skeletal Muscles

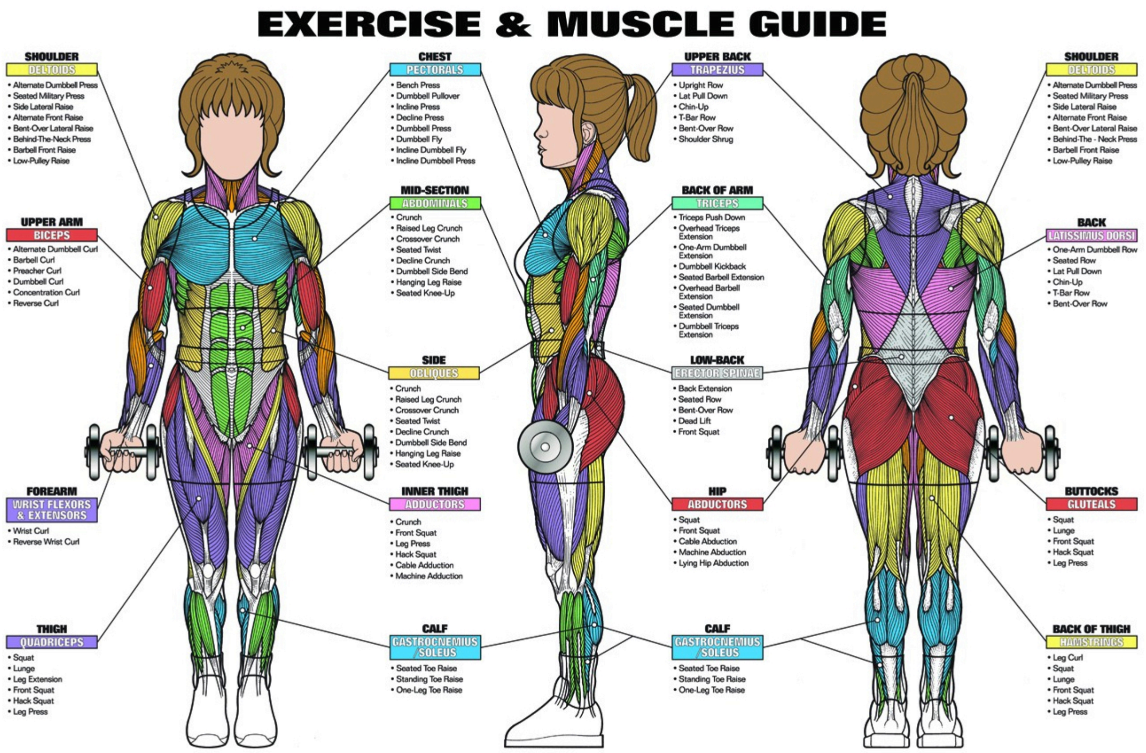
There are about 640 skeletal muscles of various sizes in the human body (Jones and Barker, 1996). The main task of skeletal muscles is to move or control bones, skin and the connective tissue, called fascia. In order to pursue this task, muscles need to utilise the chemical energy produced by one of the three metabolic systems discussed in the previous section and convert it into mechanical force (McConnell and Hull, 2011). During exercise skeletal muscle contraction provides mobility to the body by developing forces and stabilises the body by absorbing shock and supporting any changes to the centre of mass of the body (Jones and Barker, 1996; Novacheck, 1998; Hamner et al., 2010; Marieb, 2012).

Muscles can have various different shapes resulting in different levels of force and range of movement. In general, long muscles produce large external movements, whereas short muscles create smaller, more precise movements (Calais-Germain, 1993). Some muscles primarily use the aerobic system for energy production (called slow-twitch), while others predominantly use the anaerobic system (called fast-twitch). Slow-twitch muscles are generally thin and contract slowly. They also tire slowly, which makes them well suited for endurance exercise. Fast-twitch muscles contract fast and thus fatigue quickly; therefore they are well suited for explosive movements, such as sprinting. The balance of slow-twitch and fast-twitch muscle fibres differs across individuals and explains why certain individuals are more talented in endurance sports than others (McConnell and Hull, 2011).

There is a wide variety of reasons for muscle fatigue, depending on the exercise and training levels of individuals (McConnell and Hull, 2011). However, muscle fatigue is not fully understood and strongly debated in the research community with some researchers claiming lactic acid build-up as cause for muscle fatigue (Cairns, 2006), whilst others controvert this (Phillips, 2015). It is believed that muscle vibration contributes to muscle fatigue due to increased muscle activity required to damp vibrations (Coza and Nigg, 2008). When individual muscle fibres oscillate intensely, the nervous system can also be disturbed, which affects balance and muscle control (Textiles Intelligence Limited, 2014a). Applying pressure to the muscles can reduce muscle vibration and consequently lead to a decrease in muscle activity and, therefore, reduction in energy needed, potentially leading to improved performance (Coza and Nigg, 2008; Wang et al., 2013; Textiles Intelligence Limited, 2014a).

Regular exercise has a direct effect on muscles as it increases its size, strength and time to fatigue (Marieb, 2012). Anaerobic resistance training increases muscle size and can enhance muscle power by improving the ability of large muscle cells to produce ATP using creatine phosphate and glycolysis. Aerobic exercise creates muscles that are strong and have a great resistance to fatigue, however muscles do generally not increase in size (Marieb, 2012).

Females have 1% less muscle mass in their body compared to males, resulting in a lower muscle performance of women of a quarter to a third (Guyton and Hall, 2006). SCGs often apply pressures targeted to different muscle groups. The main muscle groups of the female body are shown in Appendix Figure A-1.



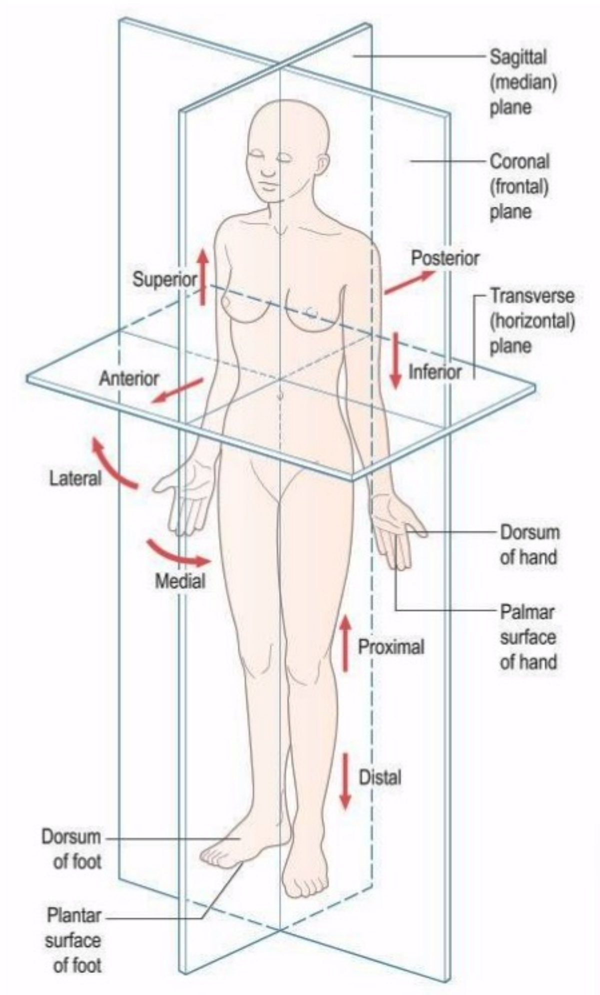
Appendix Figure A-1: Major skeletal muscle groups of the female body (Human Anatomy Diagram, 2018)

Movement of the Human Body

Movement of the human body is at the core of exercise. Movements involve interactions between bones, joints and muscles (Calais-Germain, 1993). Out of the 206 bones in the human skeleton 117 engage in voluntary movement. These bones are moved about the joints by muscles. Joints are connectors of two or more bones providing the skeleton with mobility (Marieb, 2012). The human body can be seen as a series of links, with each joint representing a link (Jones and Barker, 1996). Motion at one joint in some cases causes motion at another joint creating kinematic chains.

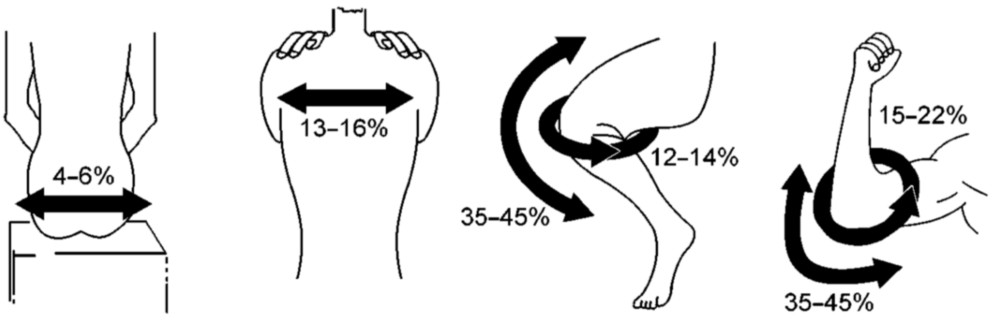
In order to describe human movement unambiguously, it is essential to understand the basics of the scientific technology used to specify movement of the human body. The human body is three-dimensional and therefore lies within three planes that are perpendicular to each other: the sagittal, frontal and transversal planes (see Appendix Figure A-2) (Calais-Germain, 1993; Jones and Barker, 1996;

Marieb, 2012). The range of movement of a body part depends on the types of joint, which are categorised by their degrees of freedom (1-3), relating to the number of planes they can move in (Jones and Barker, 1996; Bartlett, 2007). This means a joint with three degrees of freedom can move across all three planes (e.g. shoulder, hip).



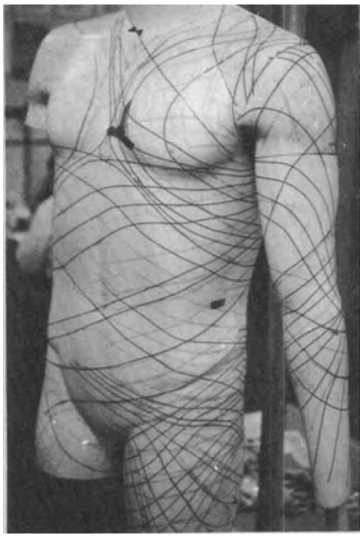
Appendix Figure A-2: Anatomical position showing the sagittal, frontal and transversal planes and terminology for directions of movement (Palastanga and Soames, 2012:2)

Movement within the three planes causes considerable skin stretch. Even during day-to-day activities skin stretch at hinge joints, such as the knees and elbows, reaches 35% and 45% respectively (Voyce et al., 2005) (see Appendix Figure A-3). These values can dramatically increase depending on the sporting activity undertaken. Chi and Kennon (2006) reported a large degree of stretch where the limbs are connected to the torso. Skin stretch variations of body lengths are generally larger than variations in body circumference measurements (Wang and Wang, 2015). Clothing needs to support these changes in skin stretch. Gill (2009) measured functional changes to the body surface in static and dynamic postures. However, not much research exists on key movement patterns for different sports disciplines and the resultant demands for clothing development (Gill and Prendergast, 2015).

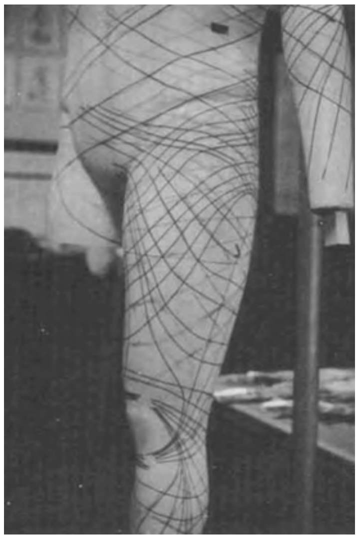


Appendix Figure A-3: Variations in body dimensions during movement (Voyce et al., 2005:205)

There are parts of the body that are not or only very minimally perceptible to changes during movements. Langer (1819-1887), a Professor of anatomy, identified tension lines, later called Langer's lines, based on the natural orientation of collagen fibrils to determine locations for incisions on the body that would result in optimal scar formation (Langer, 1861, 1862; Carmichael, 2014). Iberall's (1964) map of the body showing qualitatively measured lines of non-extension (see Appendix Figure A-4) were utilised by the US space programme in the development of pressure suits (Watkins and Dunne, 2015).



a)



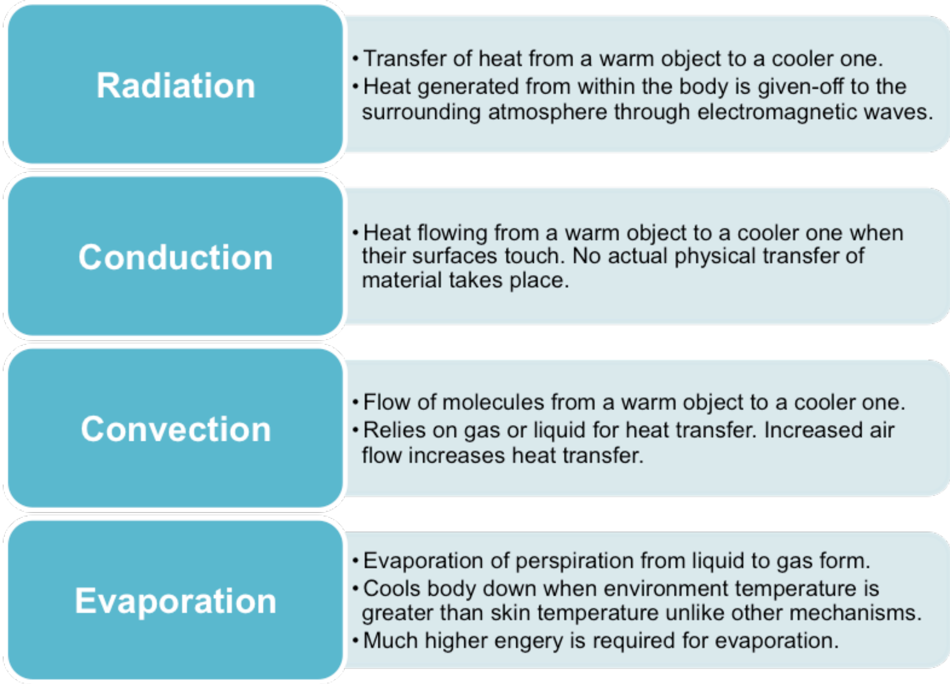
b)

Appendix Figure A-4: Lines of non-extension drawn on the upper body (a) and lower body (b) of a male mannequin. The lines were determined through surface tracing methods by measuring deformation of a surface grid after movement (Iberall, 1964:5–6).

Thermal Regulation During Exercise

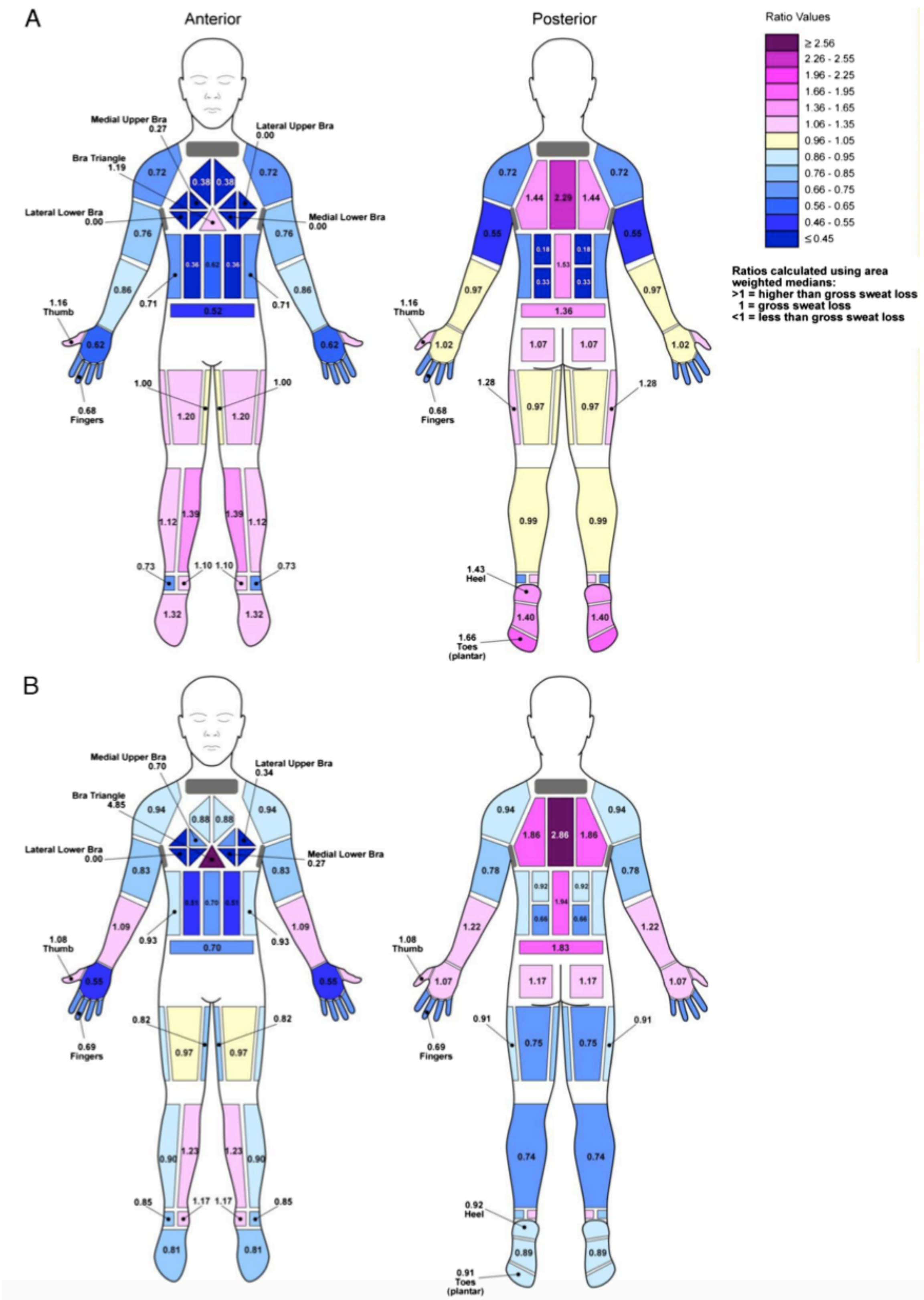
During aerobic exercise, i.e. endurance exercise, an immense amount of heat is created through the metabolic process. This heat needs to be dissipated to avoid heat stroke and to ensure the body temperature is kept within its narrow physiological limits (Shirreffs et al., 2004; Guyton and Hall, 2006). In a hot climate, where the skin temperature is lower than ambient temperature, the only way to dissipate heat is through sweat evaporation from the surface of the skin, however sweat also produces at low temperatures when the workload is high (Shirreffs et al., 2004).

Blood flow is important in order to regulate body temperature as the warm blood from the muscles flows to the body surface where the heat can dissipate (Togawa, 1985; Shirreffs et al., 2004). There are four general mechanisms of heat transfer helping the body to regulate its temperature: radiation, conduction, convection and evaporation, as described in Appendix Figure A-5.



Appendix Figure A-5: Mechanisms of heat transfer (Horn and Gurel, 1981; Watkins, 1995; Pan, 2008; Watkins and Dunne, 2015)

Smith and Havenith (2012) analysed the sweat patterns of males and females during intense exercise. Women generally sweat less than men under the same workload due to higher metabolic heat produced in men. The researchers found highest sweat rates at the central upper back for both sexes and lowest at the extremities. However, the overall sweat patterns varied slightly between males and females with males sweating slightly more in the torso region than females who had higher sweat rates at the arms, hands and feet. These variations are important in the design of gender-specific sportswear. The body map showing the normalised regional median sweat rates measured by Smith and Havenith (2012) are shown in Appendix Figure A-6.



Appendix Figure A-6: Normalized regional median sweat rates of female athletes at exercise intensity 1 (panel A) and exercise intensity 2 (panel B) (Smith and Havenith, 2012:2356)

Post-Exercise Recovery

High-intensity exercise can cause muscle damage and have stressful consequences for the human body. Post-exercise recovery is crucial to ensure performance returns to optimal levels at subsequent exercise bouts. The effects of high-intensity exercise range from short-term impairment lasting a few minutes or hours to long-term impairments that can last several days (Barnett, 2006). Short-term impairments are generally related to the replacement of metabolic substance stores, glycogen, ATP and creatine phosphate that have been exhausted during exercise. Rehydration is another important part of recovery, as dehydration before the next training session can be detrimental to performance (Shirreffs et al., 2004; Barnett, 2006).

One of the most common longer-lasting impairments after high-intensity exercise is delayed onset muscle soreness (DOMS), which can have detrimental effects on subsequent athletic performance (Cheung et al., 2003). Symptoms of DOMS vary from slight discomfort to severe pain during muscle contraction, which can lead to a reduction in range of motion, flexibility and strength (Cheung et al., 2003; French et al., 2008; Valle et al., 2013). Symptoms can start about 6 hours after exercise and can last up to 7 days, reaching peak pain levels about 48 to 72 hours after exercise (French et al., 2008). DOMS is classed as a grade 1 muscle injury and can cause more severe injuries if returning to training before recovering fully due to increased stress on muscle ligaments and tendons (Cheung et al., 2003; Valle et al., 2013). The level of symptoms depends on the type and intensity of exercise, duration of exercise and familiarisation with the exercise (Cheung et al., 2003; Hill et al., 2015). DOMS frequently appears after unaccustomed, high eccentric exercise bouts (Barnett, 2006; Valle et al., 2013). The underlying mechanism of DOMS is not yet understood. There are a number of theories about DOMS, such as the lactic acid, muscle spasm theory (Cheung et al., 2003) or structural cell damage (Armstrong, 1984), however, it is unclear if any of the theories are true or if a combination of them might cause DOMS.

Individuals respond differently to the stresses caused by high-intensity exercise; genetics and training status influence the effects. As a result, responses from elite athletes can be very different to responses from non-athletes (Barnett, 2006). It has been shown that the muscle damage caused by unfamiliar eccentric exercise is reduced significantly when the same exercise is repeated, even if there is a gap of several weeks or months between the exercise sessions. This effect is known as repeated bout effect. Nosaka et al. (2001) found that the repeated bout effect lasted at least six months for their non-athletic 35 male participants. However, it was lost between nine and twelve months. This shows that the neuromuscular system adapts to the eccentric bout of exercise in order to protect muscle from further damage. However, a full understanding of this effect has not yet been achieved (Nosaka et al., 2001).

Improving muscle recovery is an important aspect of sports performance as athletes that are not fully recovered will be impaired in their performance. Various modalities believed to support recovery are, therefore, used by most elite athletes. Even though the physical benefits of such therapies are not fully proven, perceptual aspects of recovery can play a vital role. In a longitudinal quasi-experiment of the effects of various recovery modalities (floor stretching, pool stretching, bike active recovery, pool active recovery, cold-water immersion, contrast therapy and use of SCGs) Bahnert and colleagues (2013) found that there was no association between the recovery modalities chosen by their 44 participants and physical recovery and next-game-performance. However, participants who selected a combination of cold-water immersion, floor stretching and post-game SCG usage showed a significantly higher perceptual recovery compared to participants opting for the other recovery protocols.

Appendix B. Existing research assessing the effects of sports compression garments on exercise performance and recovery

Appendix Table B-1: Existing studies on the effects of sports compression garments on exercise performance and recovery

Study reference	Background of researchers	Focus of study	Pressure determination
Ali et al. (2007)	Food, health and sports	P, R	E
Ali et al. (2010)	Food, health and sports	P, R	M
Ali et al. (2011)	Food, health and sports	P	E
Areces et al. (2015)	Sports science	P, R	E
Armstrong et al. (2015)	Sports Medicine	R	E
Bakken (2011)	Health and human development	P	NR
Barwood et al. (2013)	Sport science	P	M
Bernhardt and Anderson (2005)	Kinesiology & physical education	P	NR
Berry and McMurray (1987)	Human performance	R	E
Bieuzen et al. (2014)	Sports science	P, R	E
Bindemann (2007)	Sports science	R	E
Born et al. (2014)	Sport science	P	M
Bovenschen et al. (2013)	Medicine	R	E
Brighenti et al. (2013)	Sports and health	P	NR
Bringard et al. (2006)	Sports	P	NR
de Britto et al. (2017)	Neuromechanics	K/P	E
Brophy-Williams et al. (2017)	Sports science	R	M
Burden and Glaister, (2012)	Human Sciences	P	M, in vitro
Cabri et al. (2010)	Sports science	P	NR
Carling et al. (1995)	Physical therapy	R	NR
Chan et al. (2016)	Health	R	NR
Chatard et al. (2004)	Physiology	R	E
Coza and Nigg (2008)	Kinesiology	P	NR
Coza et al. (2012)	Kinesiology	P	C
Creasy (2008)	Sports science	P	M
Dascombe et al. (2011)	Sports and health	P	M
Dascombe et al. (2013)	Sport science	P	E
Davies et al. (2009)	Sports	R	E
De Glanville and Hamlin, (2012)	Social science, sport	R	M
Del Coso et al. (2014)	Sport Science	P	NR
Doan et al. (2003)	Biomechanics and sports	P	NR
Driller and Halson, (2013a)	Sports	R	E
Driller and Halson, (2013b)	Sports	P	E
Duffield and Portus (2007)	Human Movement	P, R	NR
Duffield et al. (2008)	Human movement, health and sports	P, R	NR
Duffield et al. (2010)	Human Movement	P, R	E
Eckert (2009)	Health	P	M, in vitro
Faulkner et al. (2013)	Sports science	P	M

Study reference	Background of researchers	Focus of study	Pressure determination
Fedorko (2007)	Health and sport	R	NR
Feil (2011)	Sports science	R	E
Ferguson et al. (2014)	Sports science	R	E
Fletcher et al. (2014)	Sports science	R	E
French et al. (2008)	Sport science	R	E
Friesenbichler (2013)	Kinesiology	P, R	C
Fu et al. (2012)	Kinesiology	P	NR
Gallaher et al. (2010)	Sports science	R	NR
Gallaher (2012)	Sports science	R	NR
Ghai et al. (2018)	Human development	R	M, in vitro
Gill et al. (2008)	Sport science	R	NR
Goh et al. (2011)	Sports	P	M
Goto and Morishima (2014)	Sport science	R	NR
Goto et al. (2017)	Sports science	R	E
Gupta et al. (2015)	Health	P	NR
Hamlin et al. (2012)	Social science, sport	R	M
Heath (2008)	Sports science	P	NR
Higgins et al. (2009)	Sports	P	NR
Hill, Howatson, van Someren, Walshe et al. (2014)	Sports science	R	M
Hill et al. (2017)	Sports science	R	M
Hooper et al. (2015)	Human performance	K/P	NR
Houghton et al. (2009)	Human movement and biomedics	P	NR
Hsu et al. (2017)	Sports science	P	M
Jakeman et al. (2010a)	Sport and health science	R	E
Jakeman et al. (2010b)	Sport and health science	R	E
Jokinen et al. (2018)	Biomedical science	R	M
Kerhervé et al. (2017b)	Sports and health science	P	M
Kemmler et al. (2009)	Medicine and sports	P	E
Kim et al. (2017)	Health	R	E
Koo and Lee (2013)	Clothing & Textiles	P	NR
Kraemer et al. (1996)	Kinesiology	P	NR
Kraemer et al. (1998a)	Sports medicine and sports science	P	NR
Kraemer et al. (1998b)	Sports medicine and sports science	P	NR
Kraemer et al. (2000)	Sports medicine	P	M, but not reported
Kraemer et al. (2001a)	Sports medicine	R	C
Kraemer et al. (2001b)	Sports medicine	R	C
Kraemer et al. (2010)	Kinesiology & Physiology	R	NR
Kurz and Anders (2018)	Motor research	K/P	E
Laymon (2009)	Health and sport	K/P	NR
Lee et al. (2017)	Clothing and brain engineering	K/P	M
Leoz-Abaurrea et al. (2016)	Health science	P	M
Leoz-Abaurrea and Aguado-Jimenez (2017)	Health science	P	E

Study reference	Background of researchers	Focus of study	Pressure determination
Lien et al. (2014)	Health science	K/P	NR
Liu et al. (2012)	Textiles	P	NR
Loturco et al. (2016)	Sports science	K/P	NR
Lovell et al. (2011)	Sports and health science	R	M
Lucas-Cuevas et al. (2015)	Sport	K/P	E
Lucas-Cuevas et al. (2017)	Sport	P	E
MacRae et al. (2012)	Clothing & Textiles and Sports	P	M
Marques-Jimenez et al. (2018)	Sports and health science	R	E
Martorelli et al. (2015)	Sports and kinesiology	P	NR
Maton et al. (2006)	Medicine	P, R	M
Menetrier et al. (2011)	Medicine	P, R	E
Michael et al. (2014)	Sports science	P	NR
Miyamoto et al. (2011)	Sports science	P	E
Miyamoto and Kawakami (2014)	Sports science	P	M
Miyamoto and Kawakami (2015)	Sports science	P	E
Mizuno et al. (2016)	Sports and health science	R	M
Mizuno et al. (2017)	Sports and health science	R	M
Montgomery et al. (2008a)	Physiology and sports	R	E
Montgomery et al. (2008b)	Physiology and sport	R	E
Nolden and Wienecke (2013)	Sports science	P, R	NR
Pareira et al. (2014a)	Sports	R	NR
Pareira et al. (2014b)	Sports	P	NR
Pearce et al. (2009)	Sports science	K/P	NR
Perrey et al. (2008)	Motor efficiency	R	NR
Piras and Gatta (2017)	Biomedical and neuromotor science	R	M
Priego Queseda et al. (2015a)	Sports biomechanics and physiology	P	E
Priego Quesada et al. (2015b)	Sports biomechanics and biophysics	P	E
Pruscino et al. (2013)	Sports and physiology	R	M
Rider et al. (2014)	Health science and human performance	P	E
Rimaud et al. (2010)	Exercise physiology	P, R	E
Rugg and Sternlicht (2013)	Human performance	P	E
Sambaher et al. (2016)	Human kinetics	P	E
Santos Cerqueira et al. (2015)	Neuro-muscular physiology	R	NR
dos Santos et al. (2016)	Health	R	E
Scanlan et al. (2008)	Health and sports	P	M
Sear et al. (2010)	Sports and health	P	M
Shimokochi et al. (2017)	Sport medicine	R	NR
Silver et al. (2009)	Health and sports medicine	P	NR
Smale et al. (2018)	Sports science	P	M
Song et al. (2016)	Human environmental studies	K/P	NR
Sperlich et al. (2010)	Sports science	P	E
Sperlich et al. (2011)	Sports science and medicine	P	M

Study reference	Background of researchers	Focus of study	Pressure determination
Sperlich et al. (2013a)	Sports science	R	M
Sperlich et al. (2013b)	Sports science	P	M
Sperlich et al. (2014)	Sports science	P	M
Stickford et al. (2015)	Kinesiology	P	E
Struhár et al. (2018)	Sports science	P, R	M, in vitro
Thedon et al. (2008)	Motor efficiency	P	M, but not reported
Tobin (2016)	Health science	P	E
Trenell et al. (2006)	Neurogenetics, sport science and medicine	R	M
Treseler et al. (2016)	Sports science	P, R	E
Tsurike and Ellenbecker (2013)	Kinesiology	K/P	NR
Tyler Cavanaugh et al. (2015)	Human kinetics	K/P	NR
Upton et al. (2017)	Sport and health	R	M
Valle et al. (2013)	General and sports medicine	R	NR
Valera-Sanz et al. (2011)	Sports	P	E
Venckunas et al. (2014)	Sports	P	M
Vercruyssen et al. (2014)	Sports	P	E
Vercruyssen et al. (2017)	Sports	P	E
Wahl et al. (2012)	Sports science and medicine	P	M
Wakeling et al. (2013)	Biomechanical physiology and kinesiology	P	NR
Wang et al. (2013)	Sports and mechanical engineering	P	NR
Wang et al. (2016)	Sports and mechanical engineering	P	NR
Wannop et al. (2016)	Kinesiology	P	NR
Welman (2011)	Sports science	R	E
Zinner et al. (2017)	Sports science	R	M

P = Performance; R = Recovery; K/P = Kinematics/Proprioception
E = Estimated pressure levels; M = Measured pressure levels; C = Calculated pressure levels; NR = Not reported pressure levels

Appendix Table B-2: Existing studies on the effects of sports compression garments on exercise performance separated by garment type and exercise type

Garment Type	Endurance	Strength	Power
Below-knee socks	Ali et al. (2007) E Ali et al. (2010) M Ali et al. (2011) E Areces et al. (2015) E Bieuzen et al. (2014)* E *(calf sleeve)* Creasy (2008) M Kerhervé et al. (2017b) M *(calf sleeve)* Kemmler et al. (2009)* E Kurz and Anders (2018)* E *(calf sleeve)* Lucas-Cuevas et al. (2017)* E Menetrier et al. (2011) E[#] Miyamoto and Kawakami (2015)* E Priego Quesada et al. (2015) E Priego Quesada et al. (2015) E Rider et al. (2014) E Rimaud et al. (2010) E Sperlich et al. (2010) E Sperlich et al. (2011) M *(calf sleeve)* Stickford et al. (2015) E *(calf sleeve)* Struhár et al. (2018)* M (*in vitro*; *calf sleeve)* Treseler et al. (2016) E Varela-Sanz et al. (2011)* E Vercruyssen et al. (2014) E Wahl et al. (2012) M	Miyamoto et al. (2011)* E	Sambaher et al. (2016)* E
Shorts	Miyamoto and Kawakami (2014)* M	Fu et al. (2012)* E *(thigh tube)*	De Britto et al. (2017) E Eckert (2009) M *(in vitro)*
Tights	Barwood et al. (2013) M Burden and Glaister (2012) M *(in vitro)* Dascombe et al. (2011) M Driller and Halson (2013b)* E Goh et al. (2011) M Hsu et al. (2017) M*	Kraemer et al. (2000)* M *(hosiery)* Maton et al. (2006) M *(full-length medical stockings)*	Born et al. (2014)* M Duffield et al. (2010) E Faulkner et al. (2013)* M Sperlich et al. (2013)* M *(calf sleeve and shorts)* Tobin (2016) E

Garment Type	Endurance	Strength	Power
	Rugg and Sternlicht (2013)* E Scanlan et al. (2008) M Smale et al. (2018) M Sperlich et al. (2010) E Venckunas et al. (2014) M Vercruyssen et al. (2017) E *(3/4 length tights)*		
Whole body	Friesenbichler (2013) C MacRea et al. (2012) M Sear et al. (2010)* M Sperlich et al. (2010) E	-	-
Top	Dascombe et al. (2013) E Leoz-Abaurrea et al. (2016) M *(short sleeved)* Leoz-Abaurrea and Aguado-Jimenez (2017) E[###]		Sperlich et al. (2014) M
Arm sleeves	-	-	-

*** = Positive effect found in study;(calf sleeve)***
E = Estimated pressure levels, M = Measured pressure levels, C = Calculated pressure levels; NR = Not reported whether pressure levels are estimated or measured
Only showing studies reporting pressure levels applied by compression garments under investigation.

Appendix Table B-3: Existing studies on the effects of sports compression garments on post-exercise recovery separated by garment type, exercise type and wear time

Garment Type	Wear Time	Endurance	Strength	Power/ Intermittent Exercise
Below-knee socks	DE	Ali et al. (2007) E Ali et al. (2010) M Areces et al. (2015) E Bovenschen et al. (2013) E Fletcher et al. (2014)* E dos Santos et al. (2016) E Treseler et al. (2016)* E Welman (2011)* E	-	-
	PE	Armstrong et al. (2015)* E Brophy-Williams et al. (2017)* M Feil (2011) E Ferguson et al. (2014) E Struhár et al. (2018)* M (*in vitro*; *calf sleeve)* Welman (2011)* E	-	-
	DPE	Berry and McMurray (1987)* E Bieuzen et al. (2014)* E[#] Bindemann (2007)* E Menetrier et al. (2011) E[#] Rimaud et al. (2010) E Welman (2011)* E	-	Marques-Jimenez et al. (2018)* E
Shorts	DE	-	-	-
	PE	Sperlich et al. (2013) M		
	DPE	-	-	-
Tights	DE	Lovell et al. (2011)* M Mizuno et al. (2017)* M	-	Marques-Jimenez et al. (2018)* E
	PE	De Glanville and Hamlin (2012)* M Driller and Halson (2013a)* E Hill, Howatson, van Someren, Walshe et	French et al. (2008) E Trenell et al. (2006)* M	Chatard et al. (2004)* E *(full-length medical stockings)* Davies et al. (2009) E

Garment Type	Wear Time	Endurance	Strength	Power/ Intermittent Exercise
		al. (2014)* M Mizuno et al. (2016)* M Montgomery et al. (2008)* E Montgomery et al. (2008) E		Hamlin et al. (2012)* M Hill et al. (2017)* M Jakeman et al. (2010b)* E Jakeman et al. (2010a)* E Jokinen et al. (2018) E Pruscino et al. (2013)* M Upton et al. (2017)* M Zinner et al. (2017)* M
	DPE	-	Maton et al. (2006) M *(full-length medical stockings)*	Duffield et al. (2010)* E Marques-Jimenez et al. (2018)* E
Whole body	DE	Friesenbichler (2013) C Piras and Gatta* (2017) M	-	Goto et al. (2017) E
	PE	-	-	-
	DPE	-		-
Top	DE	-	-	-
	PE	-	-	-
	DPE	-	-	-
Arm sleeve	DE	-	-	-
	PE	-	Carling et al. (1995) M *(in vitro)* Kim et al. (2017)* E Kraemer et al. (2001)* E Kraemer et al. (2001)* E	-
	DPE	-	-	-

** = Positive effect found in study*
DE = During exercise, PE = Post-exercise, DPE = During and post-exercise
E = Estimated pressure levels, M = Measured pressure levels; C = Calculated pressure levels
Only showing studies reporting pressure levels applied by compression garments under investigation.

Appendix C. Pressure levels reported in existing research

Appendix Table C-1: Pressure levels reported in existing research for lower body compression garments

Study reference	Type of garment	Level of pressure applied to body (mmHg)			Pressure measurement device used	Effects on	
		Ankle	Calf	Thigh		P	R
Ali et al. (2010)	Below-knee socks	11-26	8-15	-	Kikuhime (TT Meditrade, Sorø, Denmark)	O	O
Barwood et al. (2013)	Tights	-	17-20	10-11	Kikuhime	O	N/A
Born et al. (2014)	Tights with adhesive silicone stripes mimicking sports taping	-	20-22	19-20	SIGaT (Ganzoni-Sigvaris, St. Gallen, Switzerland)	++	N/A
Brophy-Williams et al. (2017)	Below-knee socks	19-22	23	-	Kikuhime	N/A	++
Creasy (2008)	Below-knee socks	15; 21; 32	12; 18; 23	-	Kikuhime	O	N/A
Dascombe et al. (2011)	Tights	-	19-22	14-16	Kikuhime	O	N/A
De Glanville and Hamlin (2012)	Tights	6	15	12	Kikuhime	N/A	++
Faulkner et al. (2013)	Tights	-	13	7	PicoPress® (Microlab, Padova, Italy)	++	N/A
	Shorts + calf sleeve	-	20	8			
Goh et al. (2011)	Tights	-	14	9	Kikuhime	O	N/A
Hamlin et al. (2012)	Tights	9	13	9	Kikuhime	N/A	++
Hill, Howatson, van Someren, Walshe et al. (2014)	Tights	-	10	19	Kikuhime	N/A	++
Hill et al. (2017)	Tights	-	15; 24	8; 15	Kikuhime	N/A	++
Hsu et al. (2017)	Tights	-	32	22	Tekscan (South Boston, MA, USA) (sensor type not reported)	+	N/A
Kerhervé et al. (2017b)	Calf sleeve	-	23	-	PicoPress®	+	N/A
Kraemer et al. (2000)	Hosiery	8-15	7-8	5-9	HARTA Hose Pressure Tester MK 2A (Segar Design, Nottingham, UK)	++	N/A

Study reference	Type of garment	Level of pressure applied to body (mmHg)			Pressure measurement device used	Effects on	
		Ankle	Calf	Thigh		P	R
Lovell et al. (2011)	Tights	20	15	-	Kikuhime	N/A	++
MacRae et al. (2012)	Whole body	-	13-15	8-11	26PCAFA1G (Honeywell, Golden Valley, MN, USA)	O	N/A
Maton et al. (2006)	Full-length medical stockings	17-24	14	7	MST MKIII (Salzmann Medico, St Gallen, Switzerland)	O	O
Miyamoto and Kawakami (2014)	Shorts	-	-	8-25	AMI3037-2B (AMI Techno, Japan)	++	N/A
Mizuno et al. (2016)	Tights	-	13	9	AMI3037-2B	N/A	++
Mizuno et al. (2017)	Tights	-	30; 15	30; 15	AMI3037-2B	++	N/A
Piras and Gatta (2017)	Whole-body suit	-	15	8	PicoPress®	N/A	++
Pruscino et al. (2013)	Tights	19	7	5	Talley Medical, Miami, FL, USA	N/A	++
Scanlan et al. (2008)	Tights	20	17	15	Kikuhime	O	N/A
Sear et al. (2010)	Tights	18	15	13	Kikuhime	+	N/A
Smale et al. (2018)	Tights	9	-	9	Kikuhime	O	N/A
	Medical stockings	22	-	15			
Sperlich et al. (2011)	Calf sleeves	21-46	14-39	-	SIGaT	O	N/A
Sperlich et al. (2013a)	Shorts (one leg cut off)	-	-	37	SIGaT	N/A	O
Sperlich et al. (2013b)	Calf sleeve and shorts	-	20-40	18-34	SIGaT	++	N/A
Trenell et al. (2006)	Tights, one leg cut off	10	17	-	Kikuhime	+	O
Upton et al. (2017)	Tights	-	14	9	Kikuhime	N/A	++
Venckunas et al. (2014)	3/4 length tights	-	17	18	I-scan (Tekscan)	O	N/A
Wahl et al. (2012)	Below-knee socks	21-46	13-40	-	SIGaT	O	N/A
Zinner et al. (2017)	Tights	-	11; 23	11; 23	SIGaT	N/A	+

P = performance; R = recovery
++ = significant positive effect; + = some positive effect; O = no positive effect
Only showing studies measuring pressure in vivo

Appendix Table C-2: Pressure levels reported in existing research for upper body compression garments

Study reference	Type of garment	Level of pressure applied to body (mmHg)			Pressure measurement device used	Effects on	
		Forearm	Upper arm	Torso		P	R
Leoz-Abbaurrea et al. (2016)	Short sleeve top	-	3	1-2	PicoPress® (Microlab, Padova, Italy)	-	N/A
MacRae et al. (2012)	Whole body	13; 9	-	-	26PCAFA1G (Honeywell, Golden Valley, MN, USA)	O	N/A
Piras and Gatta (2017)	Whole-body suit	13	10	6	PicoPress®	N/A	++
Sear et al. (2010)	Long sleeve top	7	6	5-6	Kikuhime (TT Meditrade, Sorø, Denmark)	+	N/A
Sperlich et al. (2014)	Long sleeve top	21	14	9	SIGaT (Ganzoni-Sigvaris, St. Gallen, Switzerland)	O	N/A

P = performance; R = recovery
+ = Some positive effect, O = No positive effect
Only showing studies measuring pressure in vivo

Appendix D. Studies assessing the effects of compression tights and measuring in vivo pressures

Appendix Table D-1: Identified studies measuring in vivo pressures and evaluating the effects of wearing compression tights on exercise performance

Study reference	Participants		Study design		Measured pressure level (mmHg)			Measured variables and effects of compression	Overall reported effect on performance
	Sample size, gender, age (±SD)	Training status	Exercise protocol	Tights type	Ankle	Calf	Thigh		
Barwood et al. (2013)	8, M, 21 ±2	RE	15min treadmill test at fixed speed followed by self-paced 5km time trial in hot environment (35.2°C)	Compression tights – regular size	-	20	11	Time O Skin temp O Skin temp (quadriceps) $\uparrow$ Body temp O Perceived exertion O Thermal sensation O Thermal comfort O	O
				Compression tights – oversized (one size larger than regular size)	-	17	10		
Born et al. (2014)	12, F, 25 ±3	C	30x30m sprints (1 sprint per minute)	Compression tights with adhesive silicone stripes	-	22	19	Time $\downarrow$ VO_2 O HR O Hb O Skin temp O Perceived exertion: - upper leg muscles $\downarrow$ - lower leg muscle O - whole body O	++
	12, F, 23 ±2	C	30x30m sprints (1 sprint per minute)	Compression tights with adhesive silicone stripes	-	20	20	Time $\downarrow$ Hip flexion angle $\downarrow$ Step length $\uparrow$ Step frequency O Muscle activation (rectus femoris) $\uparrow$	

Study reference	Participants		Study design		Measured pressure level (mmHg)			Measured variables and effects of compression	Overall reported effect on performance
	Sample size, gender, age (±SD)	Training status	Exercise protocol	Tights type	Ankle	Calf	Thigh		
Dascombe et al. (2011)	11, M, 28.4 ±10	C	Progressive maximal treadmill running test	Sport Skins Classic, Skins, Australia - regular size	-	19	16	HR (>12km/h) ↓ VO_2 (8-10km/h) ↑ HHb (>12km/h) ↑ TOI (>12km/h) ↓ Lact O	O
				Sport Skins Classic - undersized (one size smaller than regular size)	-	22	16		
			Time to exhaustion test at 90% VO_2max	Sport Skins Classic - regular size	-	19	16	TTE O HHb ↑ Muscle deoxygenation O RE O VO_2max O	
				Sport Skins Classic - undersized	-	22	16		
Faulkner et al. (2013)	11, M, 23.7 ± 5.7	RE	2x 400m run tests (outdoors)	A400 compression tights, Skins, Australia	-	13	7	Time O HR O Lact O Perceived exertion ↓ Perceived soreness O Wear tightness O Wear comfort O Feeling scale O Felt arousal scale O	+
				A400 compression shorts + calf sleeve, Skins, Australia	-	20	8		

Study reference	Participants		Study design		Measured pressure level (mmHg)			Measured variables and effects of compression	Overall reported effect on performance
	Sample size, gender, age (±SD)	Training status	Exercise protocol	Tights type	Ankle	Calf	Thigh		
Goh et al. (2011)	10, M, 29.0 ±10	RE	20min run at first ventilatory threshold followed by run to exhaustion at VO_2max velocity at 10°C and 32°C	Skins Sport Men's Compression Long Tights, Skins	-	14	9	TTE O VO_2 O HR O Skin temp ↑ Rectal temp O Perceived exertion (10°C) O Perceived exertion (32°C) ↓	+
Hsu et al. (2017)	8, M, 24.9 +/- 2.3	RE	40min treadmill run at 75% VO_2max velocity with 1% gradient	Custom-made	-	32	22	Lact O Muscle activation ↓ Perceived exertion O	+
Scanlan et al. (2008)	12, M, 20.5 ±3.6	C	Stepwise incremental cycling test	Unisex Sport Skins Classic, Skins	20	17	15	Anaerobic threshold O Power output ↑ HR O Lact O VO_2 O	O
			1hour cycle time trial on ergometer					Power output O HR O Lact O VO_2 O Muscle oxygenation ↑	

Study reference	Participants		Study design		Measured pressure level (mmHg)			Measured variables and effects of compression	Overall reported effect on performance
	Sample size, gender, age (±SD)	Training status	Exercise protocol	Tights type	Ankle	Calf	Thigh		
Smale et al. (2018)	15, M, 28.1 +/- 6.3	RE	4x8min increments of cycling at 30%, 50%, 70% and 85% max. power output with Stroop tasks for each increment followed by 5min rest and 4km time trial	Elite MSC compression tights, 2XU, Australia	9	-	9	Time O Middle artery blood flow velocity O HR O Lact O Reaction time O Accuracy ↑ *(85% intensity only)* Perceived exertion O Motivation O Perceived difficulty O	O
				Venosan 6000: grade III MCS, Venosan, Switzerland	22	-	15	Accuracy O *Other variables as above*	

F = female; M = male; C = competitive athlete; RE = recreational athletes

Hb = total hemoglobin; HHb = deoxyhemoglobin; HR = heart rate; Lact = blood lactate; Temp = temperature; TOI = tissue oxygenation index; TTE = time to exhaustion; VO_2 = oxygen consumption; VO_2max = maximal aerobic capacity;

O = no effects; + = some positive effect(s); ++ = significant positive effect(s) on performance

Only included studies using full length sports compression tights that measured pressures in vivo

Appendix Table D-2: Identified studies measuring in vivo pressures and evaluating the effects of wearing compression tights on post-exercise recovery

Study reference	Participants		Study design			Measured pressure level (mmHg)			Measured variables and effects of compression	Overall reported effect on recovery
	Sample size (wearing CGs), gender, age	Training status	Exercise protocol	Tights type	Time worn	Ankle	Calf	Thigh		
De Glanville and Hamlin (2012)	14, M, 33.8 ±6.8	C	40km time trials on a cycle ergometer	Skins, Australia	24h PE	6	15	12	Power output ↑ Time ↓ HR O VO_2 O Lact O Perceived exertion O	++
Hamlin et al. (2012)	22, M, 20.1 ±2.1	C	Exercise circuit designed to simulate a game of rugby, followed 24h later by 40m repeated sprint test (10 sprints at 30-sec intervals) and 3km run	Sport Skins Classic, Skins, Australia	24h PE	9	13	9	Sprint time ↓ 3km time ↓ CK O Lact ↓ HR (3km) ↓ Muscle soreness (48h) ↓	++
Hill, Howatson, van Someren, Walshe et al. (2014)	12, 8M 4F, 47.7 ±10.8	C	Marathon run	MA1551b (men's) and WA1552b (women's), 2XU, Australia	72h PE	-	19	10	Muscle soreness (1, 48, 72h) O Muscle soreness (24h) ↓ MVIC (1, 24, 48, 72h) O CK (1, 24, 48, 72h) O C-RP (1, 24, 48, 72h) O	+
Hill et al. (2017)	30, M F, NR	RE	Eccentric exercise protocol: 5x 20 drop jumps with 2min rest between sets	MA1551b (men's) and WA1552b (women's), 2XU, Australia	72h PE	-	15	8	Jump height (1, 24, 48, 72h) O MVIC O CK (1, 24, 48, 72h) O C-RP (1, 24, 48, 72h) O Mb (1, 24, 48, 72h) O Muscle soreness O	+

Study reference	Participants: Sample size (wearing CGs), gender, age	Participants: Training status	Study design: Exercise protocol	Study design: Tights type	Study design: Time worn	Measured pressure level (mmHg): Ankle	Measured pressure level (mmHg): Calf	Measured pressure level (mmHg): Thigh	Measured variables and effects of compression	Overall reported effect on recovery
				Alleviant grade II MCS, Jobskin, UK	72h PE	-	24	15	Jump height (1, 24, 28, 72h) ↑ MVIC ↑ *Other variables as above*	
Lovell et al. (2011)	25, M, 21.6 ±2.5	A	6x5min incremental treadmill test followed by active recovery (walking)	Body Science, Australia	DE	20	15	-	HR ↓ VO_2 O Respiratory exchange ratio ↑ Lact ↓ Blood pH O	++
Mizuno et al. (2016)	10, M, 21.9 ±0.6	RE	30min downhill (-10% gradient) running on treadmill at 70% VO_2max	UA Recharge Energy Leggings, Under Armour, MD, USA	24h PE	-	18	12	Jump height ↑ Leg girth O CK (1, 3, 24h) O Mb (1, 3, 24h) O Inflammatory markers (1, 3, 24h) O C-RP (1, 3, 24h) O Feeling O Muscle soreness O	++
	8, M, 21.9 ±0.6	RE	30min level (0% gradient) running on treadmill at 70% VO_2max						Jump height O *Other variables as above*	

Study reference	Participants: Sample size (wearing CGs), gender, age	Participants: Training status	Study design: Exercise protocol	Study design: Tights type	Study design: Time worn	Measured pressure level (mmHg): Ankle	Measured pressure level (mmHg): Calf	Measured pressure level (mmHg): Thigh	Measured variables and effects of compression	Overall reported effect on recovery
Mizuno et al. (2017)	8, M, 23.4 +/- 2.4	RE	120min uphill running (7% gradient) at 60% VO_2max	Custom-made, Descente, Japan - high-compression	DE	-	29	27	Jump height O HR O Lact O Mb O Bg O CK O Inflammatory markers O Perceived exertion O	++
				Custom-made, Descente - low compression	DE	-	18	16	Jump height ↑ HR ↓ Inflammatory markers ↓ *Other variables as above*	
Pruscino et al. (2013)	8, M, 21.9 ±2.3	A	Loughborough intermittent shuffle test exercise protocol to simulate hockey match	2XU, Australia	24h PE	19	7	5	Jump power O HR O Lact O CK O Perceived exertion O Muscle soreness (1, 24, 48h) ↓ Perceived recovery ↑	+
Trenell et al. (2006)	11, M, 21.2 ±3.1	RE	30min walking (6km/h) on treadmill with negative slope of 25%.	Skins, Australia	48h PE	10	17	-	PDE (1h) ↑ PDE (48h) O PME (1, 48h) O PCr/Pi O Blood pH O Muscle soreness (1, 48h) O	+

Study reference	Participants: Sample size (wearing CGs), gender, age	Participants: Training status	Study design: Exercise protocol	Study design: Tights type	Study design: Time worn	Measured pressure level (mmHg): Ankle	Measured pressure level (mmHg): Calf	Measured pressure level (mmHg): Thigh	Measured variables and effects of compression	Overall reported effect on recovery
Upton et al. (2017)	10, M, 20.8 +/- 1.9	C	Rugby simulating muscle-damaging protocol: 20x max. 20m sprints with 10m deceleration with tackle every other sprint	MA1551B, 2XU, Australia	48h PE	-	14	9	Jump height (0, 24, 48) O CK (0, 24, 48) ↓ MVIC (0, 24, 48) O Muscle soreness (0, 24, 48) ↓	+
Zinner et al. (2017)	12, M, 22 +/- 4	C	30x30m repeated and exhausting sprint exercise and 2 CMJ 48h later: 5x30m sprint and CMJ	Sigvaris, Switzerland - high compression	48h PE	-	23	23	Time O Jump height O CK (0, 24, 48h) O Urea (0, 24, 48h) O C-RP (0, 24, 48h) O Acute Recovery and Stress Scale O	+
				Sigvaris - medium compression	48h PE	-	11	11	CK (0, 24, 48h) ↓ Urea (0, 24, 48h) ↓ *Other variables as above*	

F = female; M = male; A = elite athlete; C = competitive athlete; RE = recreational athlete; DE = during exercise; PE = post-exercise; CMJ = counter movement jump; NR = not reported; Bg = blood glucose; CK = creatine kinase; C-RP = C-reactive protein; HR = heart rate; Lact = blood lactate; Mb = myoglobin; MVIC = maximal voluntary isometric contraction; PCr = phosphocreatine; PDE = phosphodiester; Pi - inorganic phosphor; PME = phosphomonoester; VO_2 = oxygen consumption;
O = no effects; + = some positive effect(s); ++ = significant positive effect(s) on post-exercise recovery
Only included studies using full length sports compression tights that measured pressures in vivo

Appendix E. Female body shape classification methods

FFIT: Female Figure Identification Technique

Hourglass:
Bust circ. – hip circ. = very low AND bust-to-waist and hips-to-waist are about equal and significant

If (bust-hips) < = 2.5cm Then
    If (hips-bust) < 9.1cm Then
        If (bust-waist) > = 22.9cm Or (hips-waist) > = 25.4cm Then
            shape = "Hourglass"

Bottom hourglass:
Hip circ. > bust circ. AND bust-to-waist and hips-to-waist are significant enough to produce a definite waistline

    If (hips-bust) > = 9.1cm And (hips-bust) < 25.4cm Then
        If (hips-waist) > = 22.9cm Then
            If (high hip/waist) < 1.193 Then
                shape = "Bottom Hourglass"

Top hourglass:
Hip circ. < bust circ. AND bust-to-waist and hips-to-waist are significant enough to produce a definite waistline

    If (bust-hips) > 2.5cm And (bust-hips) < 25.4cm Then
        If (bust-waist) > = 22.9cm Then
            shape = "Top Hourglass"

Spoon:
Larger circ. In hips and bust AND bust-to-waist ratio is lower than hourglass, AND high hip-to-waist ratio is great

    If (hips-bust) > 5.1cm Then
        If (hips-waist) > 17.8cm Then
            If (high hip/waist) > 1.193 Then
                shape = "Spoon"

Triangle:
Hip circ. > bust circ. AND hips-to-waist is small

    If (hips-bust) > = 9.1cm Then
        If (hips-waist) < 22.9cm Then
            shape = "triangle"

Inverted triangle:
Hip circ. < bust circ. AND bust-to-waist is small

    If (bust-hips)> = 9.1cm Then
        If (bust-waist) < 22.9cm Then

shape = “Inverted Triangle”

Rectangle:
Hip circ. = bust circ. AND bust-to-waist and hips-to-waist are low

If (hips-bust) < 9.1cm And (bust-hips) < 9.1cm Then
If (bust-waist) < 22.9cm And (hips-waist) < 25.4cm Then
shape = “Rectangle”

Diamond:
Average stomach/waist/abdomen circ. > bust circ.

Oval:
Average stomach/waist/abdomen circ. < bust circ.

(Simmons et al., 2004b; Lee et al., 2007)

Appendix Table E-1: Defining formulae for different body shape classification systems

	Defining Formulae – circumferences in cm				
	Triangle/Spoon	**Inverted triangle**	**Hourglass**	**Rectangle**	**Apple/Diamond**
Makhanya et al. (2014)	Mean (hip-bust) ≤ (hip - bust) ≤ max. (hip-bust)	(hip - bust) < 0	Mean (bust - waist) ≤ (bust - waist) ≤ max. (bust - waist)	Mean (bust - waist) - 3x SD < (bust - waist) < mean (bust - waist)	Minimum (bust - waist) ≤ - 3x SD
Gribbin (2014)	5.1 ≤ (hip - bust); (bust - waist) ≤ 23.5	9.1 ≤ (bust - hip); (bust - waist) ≤ 22.9	0 ≤ (bust - hip) ≤ 2.5; 22.9 ≤ (bust - waist)	Bust = hip; (bust - waist) ≤ 22.9	N/A
Rasband and Liechty (2006)	5.1 ≤ (hip - bust)	5.1 ≤ (bust - hip)	27.9 ≤ (bust - waist) OR 27.9 ≤ (hip - waist)	(bust - waist) ≤ 17.8; (hip - waist) ≤ 17.8	mid-body > hip and bust

**need to follow order, classified participants are no longer considered*

Appendix F. Sports compression garment design trends

Appendix Figure F-1: Women's compression top with colourful print (IntelliSkin, 2016)

Appendix Figure F-2: Women's compression tights with pattern design based on muscle groups (Body Science, 2018)

Appendix Figure F-3: Zoned printed compression on inside of women' compression tights (2XU, 2018)

Appendix Figure F-4: Integration of Kinesio-type taping on women's compression shorts (Enerskin, 2018)

Appendix Figure F-5: Women's recovery-specific compression tights with pouches for reusable ice packs (100% Play Harder, 2015)

Appendix Figure F-6: Integration of impact protection in women's mountain bike-specific compression top (G-Form, 2018)

Appendix G. Literature searches conducted to identify existing research on sports compression garments

The following databases were identified and used for the literature search:

- Key databases:
    - Emerald
    - ScienceDirect
    - Textile Technology Index
    - SCOPUS
    - Web of Science
    - SAGE Journals Online
    - BASE (Bielefeld Academic Search Engine)
- Other related databases:
    - Business/Consumer market:
    - Business Source Premier
    - Mintel
    - Exercise and sports science:
    - PsychINFO
    - SPORTDiscus
- Databases for theses:
    - Dart Europe
    - Ethos
    - Index of Theses
    - Networked Digital Library Theses and Dissertation
    - Postgraduate Dissertation Archive
    - Universal Index of Doctoral Dissertations in Progress
    - MMU e-space

The following literature searches were conducted on 5th March 2015:

Web of Science
TOPIC: ("compression garment*" OR "compression clothing" OR "compression*wear") AND TOPIC: (sport* OR exercise OR athlet*) Timespan: All years. – 141 results

TOPIC: (compression) AND TOPIC: (sport* OR exercise OR athlet*) AND TOPIC: (garment OR clothing OR wear)
Timespan: All years – 365 results

TOPIC: (compression) AND TOPIC: (sport* OR exercise OR athlet*) AND TOPIC: (garment OR clothing OR wear) AND TOPIC: (physiology)
Timespan: All years. – 88 results

SCOPUS
Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) – title, abstract, key words - 515 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND physiology – title, abstract, key words - 62 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (psychology* OR placebo) – title, abstract, key words - 52 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (psychology* OR placebo) NOT lymphoedema – title, abstract, key words - 35 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (textile* OR fabric OR material*) – title, abstract, key words - 95 results

Compression AND (sport* OR exercise OR athlet*) AND (textile* OR fabric* OR material*) – AND fib* - title, abstract, key words - 93 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (construction OR design OR pattern) – title, abstract, key words - 111 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (fit* OR siz* OR comfort) – title, abstract, key words - 103 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (“body scan*”) – title, abstract, key words - 0 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND (“3d body scan*”) – title, abstract, key words - 0 results

Compression AND (sport* OR exercise OR athlet*) AND (garment* OR clothing OR wear) AND “product development” – title, abstract, key words - 7 results

BASE (Bielefeld Academic Search Engine)
Compression garment – thesis – 38 results

Emerald
Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) – ANYWHERE - 765 results

Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) AND physiology – ANYWHERE – 138 results

Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) AND physiology – ABSTRACT – 0 results

Compression AND (garment OR clothing OR wear) – ABSTRACT – 26 results

Compression AND (garment OR clothing OR wear) AND siz* – ABSTRACT – 2 results

SAGE Journals Online
(compression AND clothing) AND (sport OR athet*) – all fields – 103 results

(compression AND clothing) AND (sport OR athet*) AND physiology – all fields – 20 results

compression AND (garment OR clothing) AND (sport OR athet*) – all fields – 211 results

compression AND (garment OR clothing) AND (sport OR athet*) AND siz* – all fields – 158 results

Textile Technology Index
Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) – 120 results

Science Direct
Compression AND (garment* OR clothing OR wear) – 46,513

Compression AND garment OR clothing AND (siz* OR fit) – TITLE, ABSTRACT, KEY WORDS – 9 results

Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) – TITLE, ABSTRACT, KEY WORDS - 40 results

Compression AND (garment OR clothing OR wear) AND (siz* OR fit) – TITLE, ABSTRACT, KEY WORDS - 75 results

Compression AND (garment OR clothing) AND (siz* OR fit) – TITLE, ABSTRACT, KEY WORDS - 9 results

Compression AND (garment OR clothing) AND (performance OR function) – TITLE, ABSTRACT, KEY WORDS - 22 results

Compression AND (garment OR clothing) AND ("body scan*") – TITLE, ABSTRACT, KEY WORDS - 5 results

Compression AND (garment OR clothing) AND (pressure mapping AND simulation) – TITLE, ABSTRACT, KEY WORDS - 0 results

Compression AND (garment OR clothing) AND (pressure mapping AND virtual) – TITLE, ABSTRACT, KEY WORDS - 0 results

Compression AND (garment OR clothing) AND pressure mapping – TITLE, ABSTRACT, KEY WORDS - 4 results

SPORTDiscuss
Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) - 238 results

Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) AND (function or performance) - 104 results

PsycINFO
Compression AND garment AND psychology – 0 results

Business Source Premier
Compression AND (sport* OR exercise OR athlet*) AND (garment OR clothing OR wear) – 52 results

Key words identified for further literature searches:

- Compression, pressure, pressure mapping, pressure prediction, pressure points, pressure zones
- Garments, clothing, apparel, wear
- Sportswear, sports, sporting, sport, exercise, athlete, athletic, sports science
- Performance, function, performance measurement, performance testing
- Body physiology
- Psychology, sports psychology, placebo
- Fit, size, sizing, comfort, sizing system, body shapes, athletes
- Construction, design, pattern, manufacturing, product development
- 3D body scanning, 3-dimensional body scanning, three-dimensional body scanning, body scan
- CAD, computer aided design, simulation, technology
- Virtual fit, fit prediction, virtual pressure prediction
- Textiles, fabrics, materials, composition, properties, testing
- Fibres, finishes
- Extension, recovery
- Thermal regulation
- Moisture management
- Contributing factors
- Product development model, design process

Appendix H. Development of survey questions

Appendix Table H-1: Development of questions for online survey

	Research question:	More focused question:	Most suitable question type:
Filter	Respondents should be SCG users	Filter question to ensure respondents use SCGs regularly	Dichotomous question
Wearer behaviour	What type of SCGs do the respondents wear and how do they use them?	What type of SCGs does the respondent wear?	Multiple choice with multiple answers
		Do athletes wear SCGs as base layer or outer garments?	Dichotomous question with additional question for yes
		How often does the respondent wear SCGs?	5-point Likert scale
		How long does the respondent wear CGs for?	Multiple choice drop down
Attitude towards CGs	Do SCGs have psychological effects on the respondents (e.g. body image/confidence)?	What is the respondent's attitude towards SCGs? Does wearing SCGs affect the respondent's feelings/level of confidence?	5-point Likert scale
	Do the respondents believe that SCGs can enhance their performance and/or recovery?	Does the respondent believe in SCGs?	Dichotomous question
Product preference	What do the respondents like about SCGs?	What is the respondent looking for in a SCG?	Multiple choice with multiple answers
		How important are the various garment characteristics to the respondent?	5-point Likert scale
	Are commercially available SCGs satisfactory for the respondents?	What SCG brand does the respondent wear?	Multiple choice with multiple answers
		How satisfied is the respondent with the various aspects of his/her SCG?	5-point Likert scale
		Does the SCG fulfill the respondent's overall expectations?	Dichotomous question
		Are there any garment features that the respondent is missing?	Open-ended question
User variability	Could different characteristics affect the way respondents use SCGs or the way the way they think about them?	Is the respondent male or female?	Dichotomous question
		How old is the respondent?	Multiple choice with one answer
		What is the respondent's level of training/ involvement in sport?	Multiple choice with one answer

Appendix I. Analysis of attitude scale after pilot study

Attitude scale statements used in pilot study:

1. I feel invincible when wearing compression clothing.
2. I don't need compression garments to achieve my competitive goals.
3. I feel more confident when wearing compression garments.
4. Wearing compression garments doesn't improve my ability as an athlete.
5. I feel more comfortable with my body when wearing compression garments.
6. Wearing compression clothing doesn't affect my mood.
7. I don't like the feeling of wearing compression garments.
8. Wearing compression garments improves my performance.
9. Wearing compression garments shortens my recovery time.
10. The promotional claims of compression garment brands are deceptive.
11. I achieve my goals faster when wearing compression garments.
12. I feel self-conscious when wearing compression garments.
13. The beneficial effects of compression garments are overrated.
14. Compression garments allow me to achieve my greatest potential.
15. I have a stronger belief in myself when wearing compression garments.
16. I don't believe the science behind compression clothing.

After reverse-scoring negatively worded statements in the scale (items 2, 4, 6, 7, 10, 12, 13, 16), reliability statistics of the attitude scale used in the pilot study were calculated using SPSS:

Appendix Table I-1: Cronbach's alpha for attitude scale in pilot study

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.790	.826	16

Appendix Table I-2: Inter-item correlation matrix for attitude scale in pilot study

	I don't need compression garments to achieve my competitive goals.	Wearing compression garments doesn't improve my ability as an athlete.	Wearing compression clothing doesn't affect my mood.	The promotional claims of compression garment brands are deceptive.	I feel self-conscious when wearing compression garments.	The beneficial effects of compression garments are overrated.	I don't believe the science behind compression clothing.	I don't like the feeling of wearing compression garments.	I feel invincible when wearing CGs.	I feel more confident when wearing CGs.	I feel more comfortable with my body when wearing CGs.	Wearing CGs improves my performance.	Wearing CGs shortens my recovery time.	I achieve my goals faster when wearing CGs.	CGs allow me to achieve my greatest potential.	I have a stronger belief in myself when wearing CGs.
I don't need compression garments to achieve my competitive goals.	1.000	.257	.000	.371	-.490	.134	-.204	-.171	.250	.149	.436	.218	.384	.444	.312	.333
Wearing compression garments doesn't improve my ability as an athlete.	.257	1.000	-.066	.828	-.151	.733	.490	-.044	.129	.511	.112	.767	.373	.705	.723	.419
Wearing compression clothing doesn't affect my mood.	.000	-.066	1.000	.071	-.151	-.068	.052	-.703	-.192	-.095	.531	-.168	-.311	-.270	-.380	.014
The promotional claims of compression garment brands are deceptive.	.371	.828	.071	1.000	-.473	.695	.606	-.032	.093	.415	.284	.891	.309	.681	.667	.475
I feel self-conscious when wearing compression garments.	-.490	-.151	-.151	-.473	1.000	.236	.120	.235	-.564	.000	-.385	-.492	-.151	-.349	-.184	-.022
The beneficial effects of compression garments are overrated.	.134	.733	-.068	.695	.236	1.000	.600	.298	-.367	.598	.117	.554	.274	.535	.543	.535
I don't believe the science behind compression clothing.	-.204	.490	.052	.606	.120	.600	1.000	-.140	-.102	.000	-.089	.579	.052	.272	.383	.272

	I don't need compression garments to achieve my competitive goals.	Wearing compression garments doesn't improve my ability as an athlete.	Wearing compression clothing doesn't affect my mood.	The promotional claims of compression garment brands are deceptive.	I feel self-conscious when wearing compression garments.	The beneficial effects of compression garments are overrated.	I don't believe the science behind compression clothing.	I don't like the feeling of wearing compression garments.	I feel invincible when wearing CGs.	I feel more confident when wearing CGs.	I feel more comfortable with my body when wearing CGs.	Wearing CGs improves my performance.	Wearing CGs shortens my recovery time.	I achieve my goals faster when wearing CGs.	CGs allow me to achieve my greatest potential.	I have a stronger belief in myself when wearing CGs.
I don't like the feeling of wearing compression garments.	-.171	-.044	-.703	-.032	.235	.298	-.140	1.000	-.343	.383	-.299	.075	.176	.152	.214	.057
I feel invincible when wearing CGs.	.250	.129	-.192	.093	-.564	-.367	-.102	-.343	1.000	.000	.055	.327	.128	.250	.156	.111
I feel more confident when wearing CGs.	.149	.511	-.095	.415	.000	.598	.000	.383	.000	1.000	.488	.488	.477	.580	.582	.745
I feel more comfortable with my body when wearing CGs.	.436	.112	.531	.284	-.385	.117	-.089	-.299	.055	.488	1.000	.286	.531	.461	.307	.461
Wearing CGs improves my performance.	.218	.767	-.168	.891	-.492	.554	.579	.075	.327	.488	.286	1.000	.531	.824	.818	.461
Wearing CGs shortens my recovery time.	.384	.373	-.311	.309	-.151	.274	.052	.176	.128	.477	.531	.531	1.000	.868	.820	.299
I achieve my goals faster when wearing CGs.	.444	.705	-.270	.681	-.349	.535	.272	.152	.250	.580	.461	.824	.868	1.000	.885	.383
CGs allow me to achieve my greatest potential.	.312	.723	-.380	.667	-.184	.543	.383	.214	.156	.582	.307	.818	.820	.885	1.000	.538
I have a stronger belief in myself when wearing CGs.	.333	.419	.014	.475	-.022	.535	.272	.057	.111	.745	.461	.461	.299	.383	.538	1.000

Appendix Table I-3: Summary of inter-item correlations for attitude scale in pilot study

Summary Item Statistics							
	Mean	**Min.**	**Max.**	**Range**	**Max./Min.**	**Variance**	**N of Items**
Inter-Item Correlations	.229	-.703	.891	1.594	-1.269	.128	16

Appendix Table I-4: Item-total statistics for attitude scale in pilot study

Item-Total Statistics				
	Scale Mean if Item Deleted	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Cronbach's Alpha if Item Deleted**
I don't need compression garments to achieve my competitive goals.	48.20	43.289	.272	.790
Wearing compression garments doesn't improve my ability as an athlete.	48.00	35.778	.740	.743
Wearing compression clothing doesn't affect my mood.	48.90	50.767	-.278	.822
The promotional claims of compression garment brands are deceptive.	48.30	42.233	.762	.763
I feel self-conscious when wearing compression garments.	47.80	51.956	-.318	.838
The beneficial effects of compression garments are overrated.	48.40	40.267	.728	.756
I don't believe the science behind compression clothing.	47.60	45.378	.364	.783
I don't like the feeling of wearing compression garments.	47.40	46.711	-.003	.820
I feel invincible when wearing CGs.	48.80	47.733	-.023	.807
I feel more confident when wearing CGs.	47.70	41.122	.723	.759
I feel more comfortable with my body when wearing CGs.	47.50	45.389	.393	.782
Wearing CGs improves my performance.	47.80	37.956	.780	.745
Wearing CGs shortens my recovery time.	47.90	40.989	.618	.763
I achieve my goals faster when wearing CGs.	47.90	37.433	.848	.740
CGs allow me to achieve my greatest potential.	47.90	40.322	.863	.752
I have a stronger belief in myself when wearing CGs.	47.90	39.656	.638	.758

Cronbach's alpha was used to measure the internal consistency of the attitude scale. A Cronbach's alpha value of 0.79 is an acceptable result (DeVellis, 2012), however a result of >0.8 would be preferable (Pallant, 2013).

Low and negative inter-item correlation values were detected in Appendix Table H-2 (highlighted in grey), indicating that the statements with a large number of negative or low inter-item correlation values do not measure the same underlying construct (Pallant, 2013).

Item-total correlations were used to assess the degree to which each statement's score correlates with the total score (Pallant, 2013). The item-total statistics in Appendix Table H-4 show that Cronbach's alpha is higher (>0.8) if the statements highlighted in grey are deleted from the scale. These statements correspond with the statements demonstrating low or negative inter-item correlations in Appendix Table H-2.

Based on these statistical results, four of the highlighted statements in Appendix Table H-2 were deleted from the scale reducing the scale from 16 to 12 items. Statement 7 'I don't like the feeling of wearing compression garments.' was changed to 'I feel restricted when wearing compression garments.' to avoid any ambiguity in meaning.

The final version of the attitude scale contained the following statements:

1. I don't need compression garments to achieve my competitive goals.
2. I feel more confident when wearing compression garments.
3. Wearing compression garments doesn't improve my ability as an athlete.
4. I feel more comfortable with my body when wearing compression garments.
5. I feel restricted when wearing compression garments.
6. Wearing compression garments improves my performance.
7. Wearing compression garments shortens my recovery time.
8. The promotional claims of compression garment brands are deceptive.
9. I achieve my goals faster when wearing compression garments.
10. The beneficial effects of compression garments are overrated.
11. Compression garments allow me to achieve my greatest potential.
12. I have a stronger belief in myself when wearing compression garments.

Appendix J. Final version of online survey

Survey on Compression Garments for Sports Activities

I am a Doctoral Researcher at Manchester Metropolitan University, where I am carrying out a study into sports compression garments. If you are a sports compression garment user, I would be very grateful if you could complete the following online questionnaire. It should only take about 10 minutes to complete. There are no right or wrong answers. In most cases it is simply a case of ticking a box. Please try to answer all questions as accurately as possible.

This study explores athletes' perceptions regarding compression garments and their product preferences. It seeks to determine user needs and core values, which will help in the development of enhanced, functional compression garments designed to meet athletes' needs.

Your participation in this survey is voluntary and the data collected remain confidential.

Thank you for taking the time to complete this survey.

If you have any questions about the study or the way the data will be used, please feel free to contact me at kristina.brubacher@stu.mmu.ac.uk.

Kristina Brubacher

Doctoral Researcher

Department of Apparel

Manchester Metropolitan University

Q1 Do you wear compression garments as part of your training routine?

❍ Yes
❍ No

Display logic: Answer If Do you wear compression garments as part of your training routine? No Is Selected

Q1a Why do you not use sports compression garments?

Skip logic: If Why do you not use sports compression garments? Is Displayed, Then Skip To Thank you for your interest in partic...

Q2 What type of compression garment(s) do you usually wear? Please select all that apply.

❑ Long sleeve top
❑ Short sleeve top
❑ Tank top
❑ Crop top/bra
❑ Long tights
❑ 3/4 tights
❑ Shorts
❑ Body suit long
❑ Body suit short
❑ Arm sleeves
❑ Leg sleeves
❑ Socks
❑ Other - Please specify: ____________________

Q3 When you wear your compression garment(s), do you usually wear additional clothing over them?

- ❍ Yes
- ❍ No

Display logic: Answer If When you wear your compression garment(s), do you usually wear additional clothing over them? Yes Is Selected

Q3a What type of clothing do you usually wear over your compression garment(s)?

Q4 How often do you wear compression garments in the following situations?

	Always	Often	Sometimes	Rarely	Never
Competitive events	❍	❍	❍	❍	❍
Training	❍	❍	❍	❍	❍
Recovery	❍	❍	❍	❍	❍

Q5 On average, how many hours do you wear your compression garment for at any one time?

- ❍ 1 hour
- ❍ 2 hours
- ❍ 3 hours
- ❍ 4 hours
- ❍ 5 hours
- ❍ 6 hours
- ❍ 7 hours
- ❍ 8 hours
- ❍ 9 hours
- ❍ 10 hours
- ❍ 11 hours
- ❍ 12 hours
- ❍ 13 hours
- ❍ 14 hours
- ❍ 15 hours
- ❍ 16 hours
- ❍ 17 hours
- ❍ 18 hours
- ❍ 19 hours
- ❍ 20 hours
- ❍ 21 hours
- ❍ 22 hours
- ❍ 23 hours
- ❍ 24 hours
- ❍ More than 24 hours

Q6 Please indicate to what extent you agree or disagree with the following statements:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I don't need compression garments to achieve my athletic aims.	❍	❍	❍	❍	❍
I feel more confident when wearing compression garments.	❍	❍	❍	❍	❍
Wearing compression garments doesn't improve my ability as an athlete.	❍	❍	❍	❍	❍
I feel more comfortable with my body when wearing compression garments.	❍	❍	❍	❍	❍
I feel restricted when wearing compression garments.	❍	❍	❍	❍	❍
Wearing compression garments improves my performance.	❍	❍	❍	❍	❍
Wearing compression garments shortens my recovery time.	❍	❍	❍	❍	❍
The promotional claims of compression garment brands are deceptive.	❍	❍	❍	❍	❍
I achieve my goals faster when wearing compression garments.	❍	❍	❍	❍	❍
The beneficial effects of compression garments are overrated.	❍	❍	❍	❍	❍
Compression garments allow me to achieve my greatest potential.	❍	❍	❍	❍	❍

I have a stronger belief in myself when wearing compression garments.	❍	❍	❍	❍	❍

Q7 Do you believe that compression garments improve athletic performance?

❍ Yes
❍ No

Q8 Do you believe that compression garments improve post-exercise recovery?

❍ Yes
❍ No

Q9 What are your reasons for wearing compression garments? Please select all that apply.

❑ Improving comfort
❑ Improving temperature control
❑ Enhancing endurance
❑ Enhancing strength
❑ Extending time to fatigue
❑ Reducing post-exercise muscle soreness
❑ Preventing injury
❑ Minimising muscle vibration
❑ Improving sense of movement
❑ Speeding up recovery
❑ Enhancing figure
❑ Other - Please specify: ____________________

Q10 How important are the following compression garment characteristics to you?

	Very Important	Somewhat Important	Neither Important nor Unimportant	Somewhat Unimportant	Very Unimportant
Design/style	❍	❍	❍	❍	❍
Comfort	❍	❍	❍	❍	❍
Functionality	❍	❍	❍	❍	❍
Moisture management	❍	❍	❍	❍	❍
Breathability	❍	❍	❍	❍	❍
Fit	❍	❍	❍	❍	❍
Thermal regulation	❍	❍	❍	❍	❍
Easy care properties	❍	❍	❍	❍	❍
Durability	❍	❍	❍	❍	❍
Anti-odour properties	❍	❍	❍	❍	❍
Quality	❍	❍	❍	❍	❍
UV protection	❍	❍	❍	❍	❍
Soft handfeel	❍	❍	❍	❍	❍
Level of compression	❍	❍	❍	❍	❍

Q11 What brand(s) of compression garments do you usually wear? Please select all that apply.

- ❑ 110% Play Harder
- ❑ 2XU
- ❑ Adidas
- ❑ Asics
- ❑ Body Science
- ❑ Canterbury
- ❑ Compressport
- ❑ CW-X
- ❑ Nike
- ❑ Sigvaris
- ❑ Skins
- ❑ Under Armour
- ❑ X-Bionic
- ❑ Zensah
- ❑ Other - Please specify: ____________________

Q12 When you buy a new compression garment, how do you choose between the different garments on offer?

- ❍ I choose the garment with the lowest price or best value for money.
- ❍ I choose the garment with the most detailed information about the technical functionality and level of applied pressure.
- ❍ I choose the garment with the best style or colour.
- ❍ I choose the garment from the brand with the best reputation.
- ❍ I choose the garment that fits me best.

Q13 How satisfied are you with the following aspects of the compression garment that you most frequently wear?

	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
Design/style	❍	❍	❍	❍	❍
Comfort	❍	❍	❍	❍	❍
Functionality	❍	❍	❍	❍	❍
Moisture management	❍	❍	❍	❍	❍
Breathability	❍	❍	❍	❍	❍
Fit	❍	❍	❍	❍	❍
Thermal properties	❍	❍	❍	❍	❍
Aftercare properties	❍	❍	❍	❍	❍
Durability	❍	❍	❍	❍	❍
Ease of movement when wearing the garment	❍	❍	❍	❍	❍
Hand feel	❍	❍	❍	❍	❍
Quality	❍	❍	❍	❍	❍
Level of compression	❍	❍	❍	❍	❍

Q14 Does the garment fulfil your overall expectations?

❍ Yes
❍ No

Q15 What features do you wish your compression garment had that you cannot currently find on the market?

Finally, I would like to ask a few questions about you to help interpret the results.

Q16 What type of sport do you primarily participate in?

Q17 On average, how many hours a week do you train?

❍ 1 hour
❍ 2 hours
❍ 3 hours
❍ 4 hours
❍ 5 hours
❍ 6 hours
❍ 7 hours
❍ 8 hours
❍ 9 hours
❍ 10 hours
❍ 11 hours
❍ 12 hours
❍ 13 hours
❍ 14 hours
❍ 15 hours
❍ 16 hours
❍ 17 hours
❍ 18 hours
❍ 19 hours
❍ 20 hours
❍ 21 hours
❍ 22 hours
❍ 23 hours
❍ 24 hours
❍ 25 hours
❍ 26 hours
❍ 27 hours
❍ 28 hours
❍ 29 hours
❍ 30 hours
❍ More than 30 hours

Q18 When did you start training at this frequency?

- ❍ less than 1 year ago
- ❍ 1 year ago
- ❍ 2 years ago
- ❍ 3 years ago
- ❍ 4 years ago
- ❍ 5 years ago
- ❍ 6 years ago
- ❍ 7 years ago
- ❍ 8 years ago
- ❍ 9 years ago
- ❍ 10 years ago
- ❍ 11 years ago
- ❍ 12 years ago
- ❍ 13 years ago
- ❍ 14 years ago
- ❍ 15 years ago
- ❍ 16 years ago
- ❍ 17 years ago
- ❍ 18 years ago
- ❍ 19 years ago
- ❍ 20 years ago
- ❍ more than 20 years ago

Q19 How many competitive sporting events have you participated in over the past 12 months?

- ❍ None
- ❍ 1
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5
- ❍ 6
- ❍ 7
- ❍ 8
- ❍ 9
- ❍ 10
- ❍ 11
- ❍ 12
- ❍ 13
- ❍ 14
- ❍ 15
- ❍ 16
- ❍ 17
- ❍ 18
- ❍ 19
- ❍ 20
- ❍ 21
- ❍ 22
- ❍ 23
- ❍ 24
- ❍ More than 24

Q20 What is the highest level that you compete at?

- ❍ Recreational
- ❍ Club
- ❍ Regional
- ❍ National
- ❍ International
- ❍ I don't participate in competitive sporting events

Q21 What is your gender?

- ❍ Male
- ❍ Female

Q22 What is your age?

- ❍ < 20 years
- ❍ 20-40 years
- ❍ 41-60 years
- ❍ > 60 years

Q23 Where do you live?

- ❍ United Kingdom
- ❍ Europe (except UK)
- ❍ Other - Please specify: ____________________

If you have any comments that you would like to add about any of the survey questions or compression garments in general, please use the space below.

There is further opportunity to support the development of smart compression garments and experience latest technologies used in these developments. If you are a female athlete who would like to take part in future wearer trials at Manchester Metropolitan University, please provide your name and email details below. Your contact information will not be shared.

Your contact details

Name:
Email address:

Please click the 'Next' button to submit your responses.

Display logic: Answer If Do you wear compression garments as part of your training routine? No Is Selected

Thank you for your interest in participating in this survey, but the remaining questions are not relevant to you because you stated that you are not a sports compression garment user. Please click the 'Next' button to submit your responses.

Note: Skip logic (highlighted in light grey) and display logic (highlighted in light blue) is performed automatically by the online software Qualtrics and therefore invisible to respondents.

Appendix K. Survey distribution

Email to athletics clubs for survey distribution:

Dear Sir/Madam,

I am a Doctoral Researcher at the Manchester Metropolitan University, where I am carrying out a study into sports compression garments within the Department of Apparel, Hollings. The study focuses on the development of smart compression garments and seeks to determine user needs and core values, which will aid in the development of enhanced, functional compression garments designed to meet athletes' needs.

I am contacting you to ask for your kind assistance in distributing my online survey. I would like to invite the members of your athletic club to support this research by providing us with their views on compression garments and product preferences. I would, therefore, be very grateful if you could circulate this email to your club members.

The survey can be found online here:

https://qtrial2013.qualtrics.com/SE/?SID=SV_3w7xmPPz1GLxRtj

Whilst some research attempt to measure the effects of sports compression garments, knowledge about athletes’ perceptions of compression garments and whether existing garments fulfil athletes’ needs and expectations is currently lacking. Your involvement will help build this knowledge and shape the future of enhanced compression garments that support athletes in their sporting activities. Using state of the art technologies within the university, the research will measure, test and develop smart compression garments that will address and provide more efficiency and an enriched performance to users. There may be opportunities to trial compression garments and to experience the latest technologies used to develop these at a later stage of the research.

Data collected remain confidential. If you have any questions about the survey or the way the data will be used, please don't hesitate to contact me at kristina.brubacher@stu.mmu.ac.uk.

Thank you for your time and support.

Kind regards,
Kristina Brubacher

Doctoral Researcher
Department of Apparel, Hollings Faculty
Manchester Metropolitan University
Righton Building, Cavendish Street, Manchester, M15 6BG

P.S. Should you not be the right person for me to contact, I would be very grateful if you could provide me with the details of the most appropriate contact person in this matter, or if you could kindly pass on the details. Many thanks.

Online survey link distribution

The survey link was shared within the researcher's LinkedIn and Twitter networks and was distributed in the following online forums and Facebook pages/groups:

Online forums:
Runnersforum.co.uk – Running discussions – Equipment – Clothing
Therunningbug.co.uk – Running advice and chat forum
220triathlon.com – Triathlon gear forum

Facebook pages:
Parkrun UK
Runbritain.com
England Athletics
This Girl Can
British Triathlon
220 Triathlon Magazine

GreaterSport

Tough Mudder UK

Mudstacle

Nerd Fitness

Facebook groups:

Chorlton Runners

Manchester Hawks Korfball

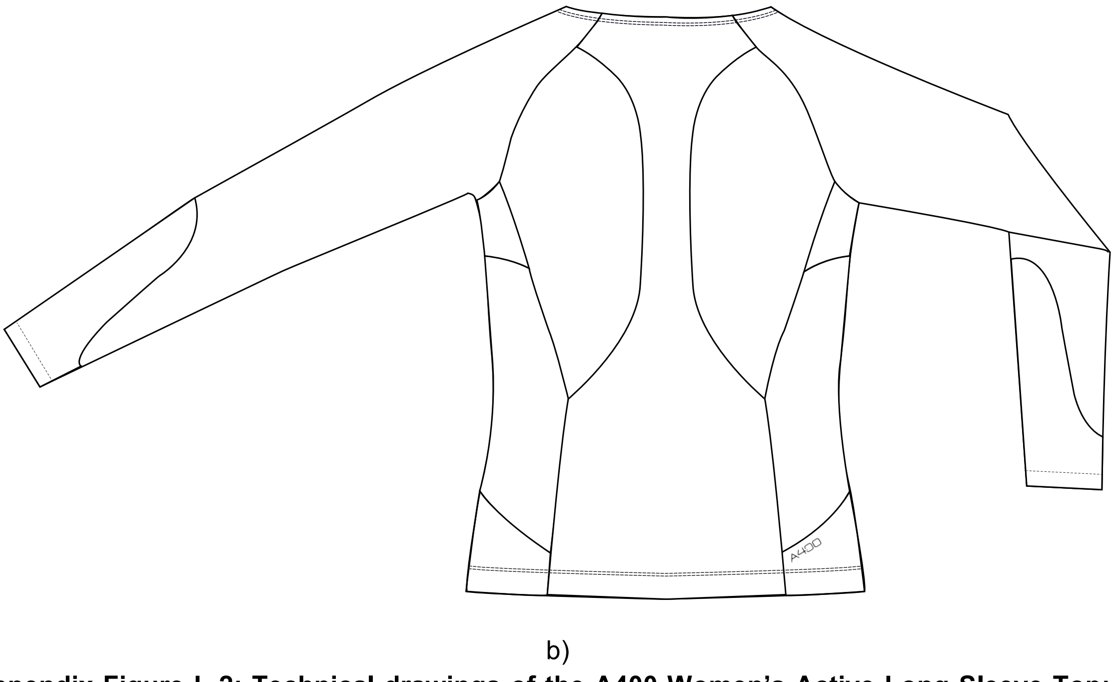
Appendix L. Skins A400 women's sports compression garments

Skins (2016) claim that "A400s boost your natural performance by delivering more oxygen and reducing lactic acid in your muscles, so you can up your own intensity without worrying too much about the next-day muscle strain." The Skins A400 range was developed in collaboration with scientific and industrial research organisations in Australia measuring compression on the human body in motion and designing gradient compression accordingly (Skins, 2016). At the time the SCGs were acquired (January 2016), Skins marketed their A400 products as "the best sports compression wear yet" (Skins, 2016). The A400 Women's Active Long Tights and Women's Active Long Sleeve Tops feature a plain-coloured, black design with subtle reflective graphics that appear gold-coloured in bright light conditions as shown in Appendix Figure L-1. The long tights target leg muscles from calf to upper thigh, whilst the long sleeve top is designed to support the core and arm muscles. The garments are equipped with the following features, as claimed by the manufacturer (Skins, 2016):

- Targeted, dynamic gradient compression that is meant to increase circulation to increase oxygen levels in active muscles,
- Memory MX fabric with unique high stretch elastomeric yarn returning to its original shape after wear,
- ADAPTIVE by HeiQ fabric treatment allows fabric to dynamically respond to the changing temperature and moisture conditions during use,
- Specifically developed A-seams for reduced chafing and bonded seams at the cuffs,
- Low rise and wide waistband of tights for improved comfort and flattering fit,
- Silicone grip on the hem to prevent tops from riding up,
- Reflective graphics using premium glass bead technology offering 360-degree reflectivity from up to 160 metre distance,
- SPF 50+ UV protection.

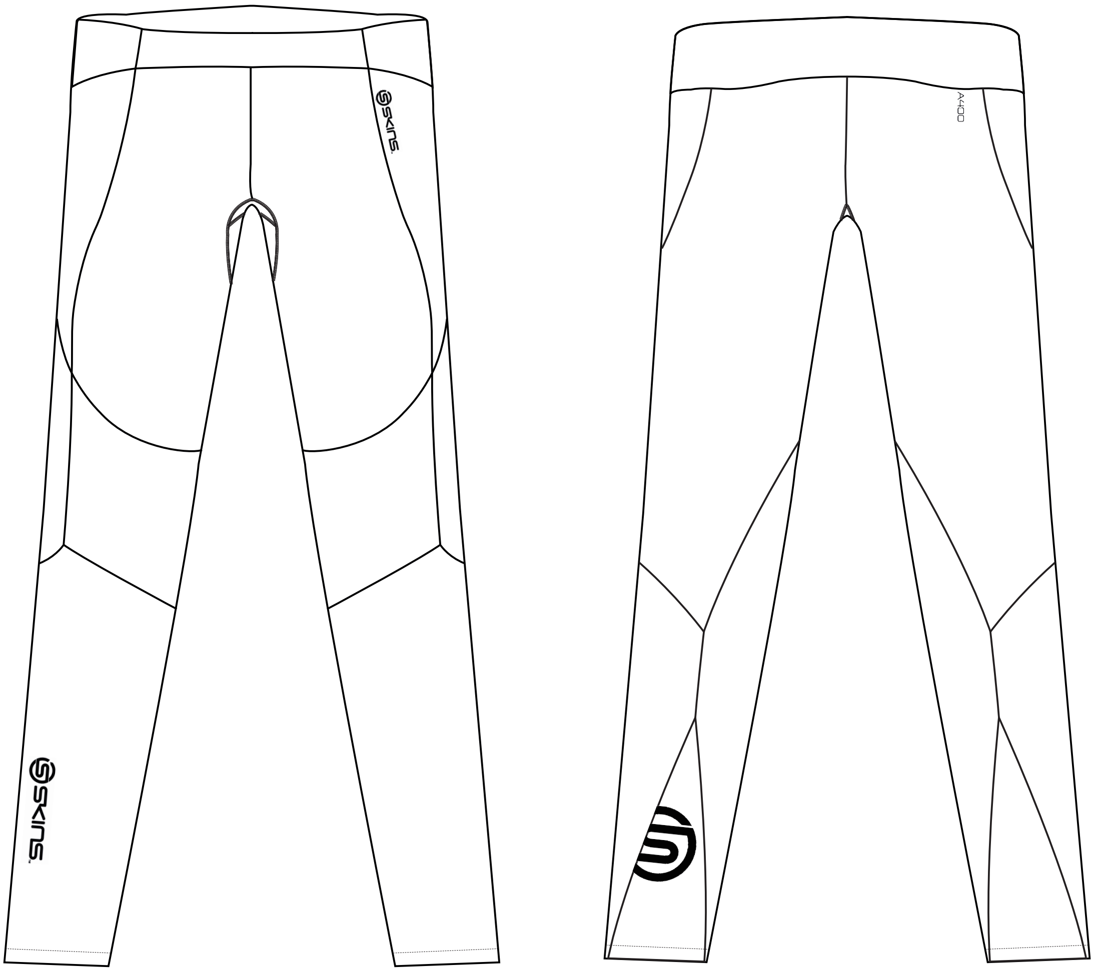
Appendix Figure L-1: Skins A400 Women's Active Long Sleeve Top and Long Tights

a)



b)

Appendix Figure L-2: Technical drawings of the A400 Women’s Active Long Sleeve Top: a) front view; b) back view



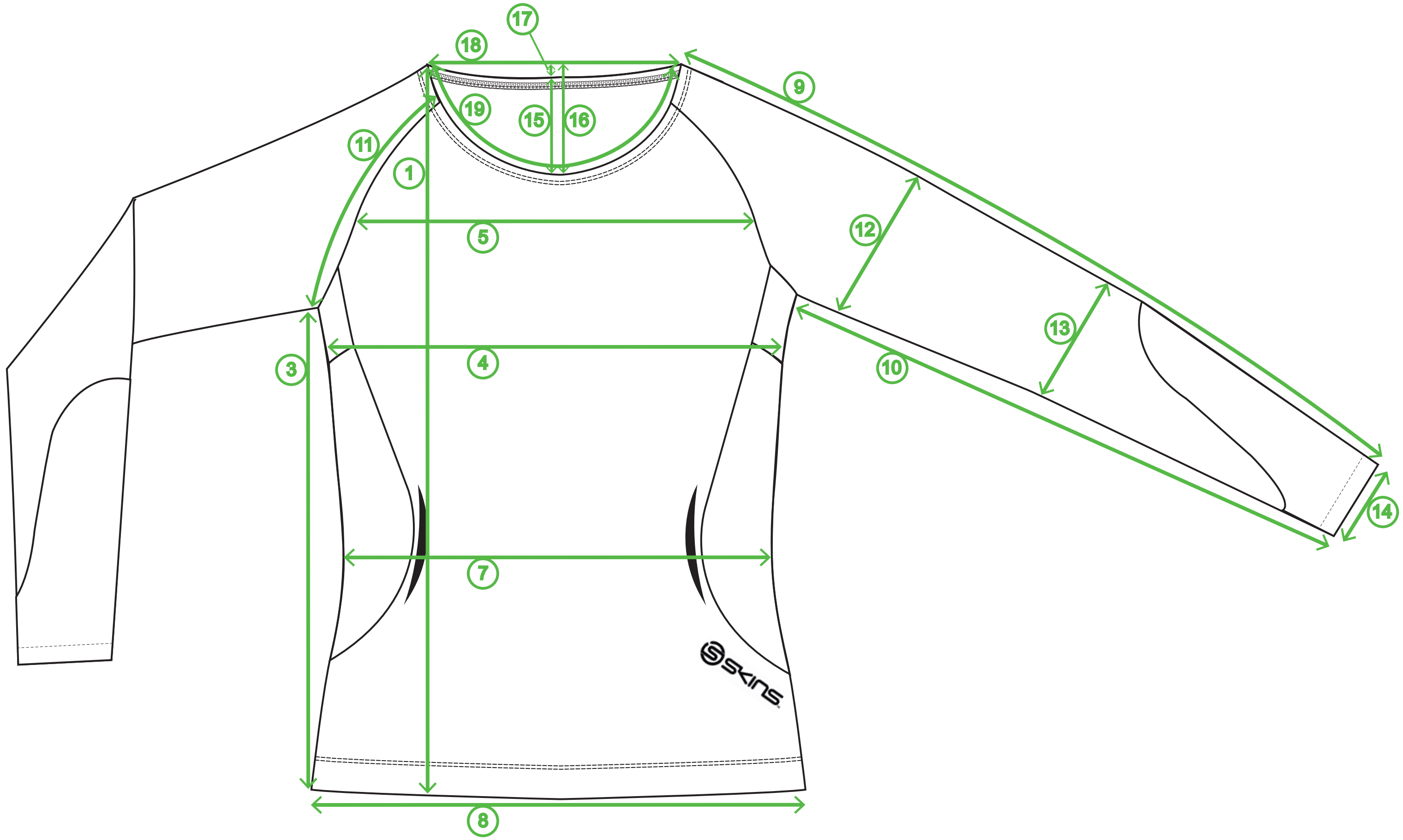
a) b)

Appendix Figure L-3: Technical drawings of the A400 Women's Active Long Tights: a) front view; b) back view

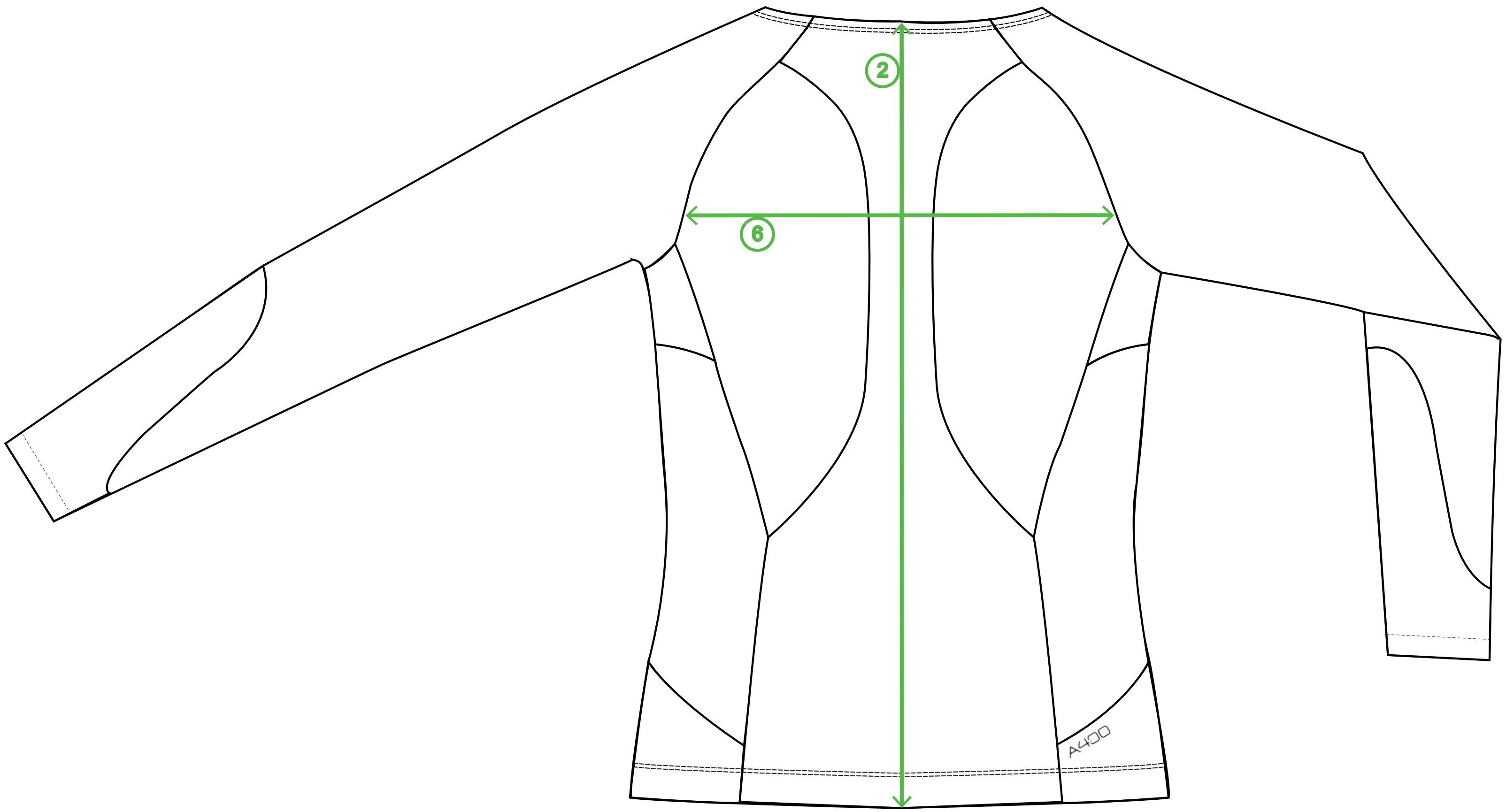
Appendix M. Garment flat measurements used to analyse sports compression garments in Study 2

Appendix Table M-1: Selected garment flat measurements for compression top and tights

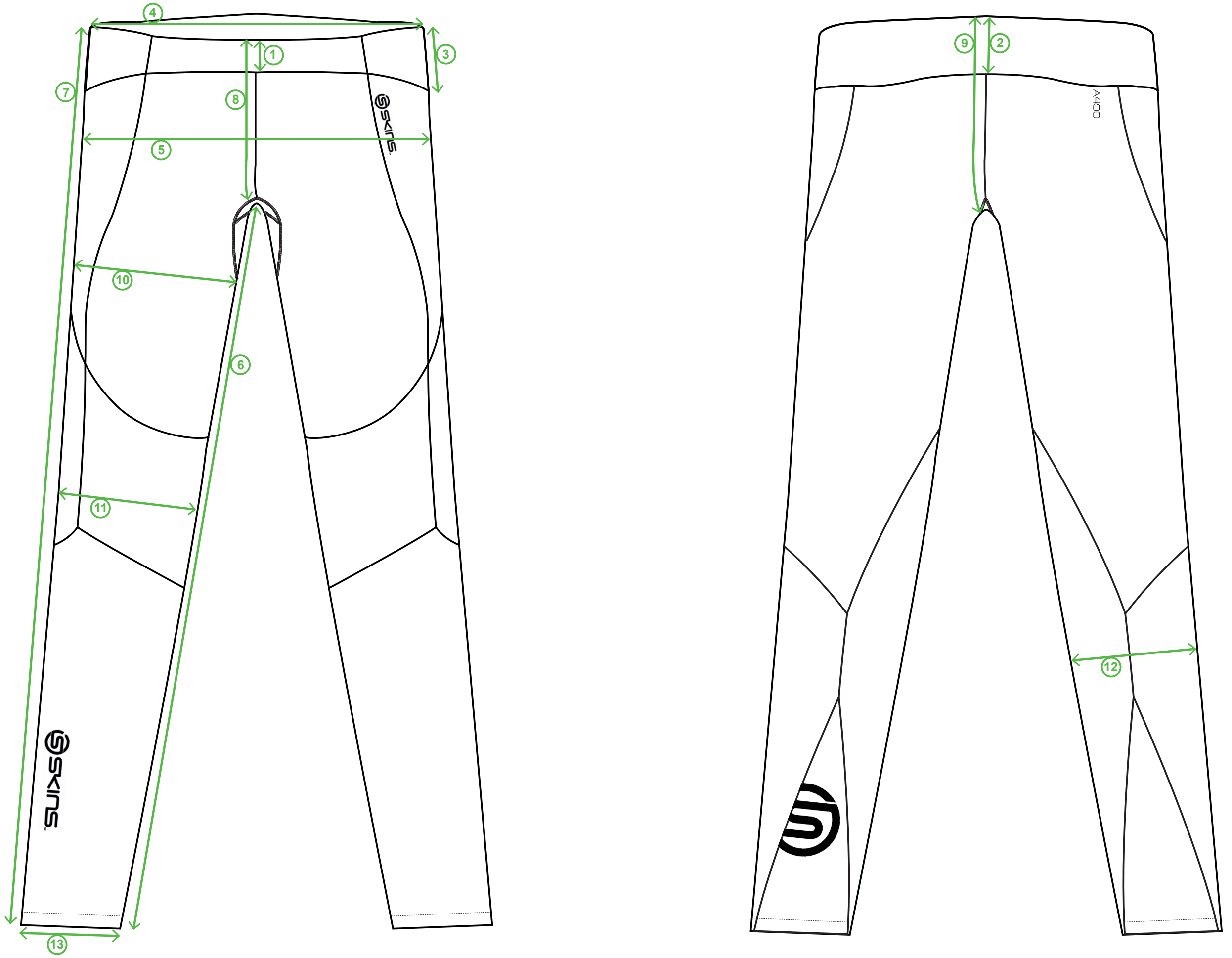
#	Compression Top - Point of Measure	#	Compression Tights - Point of Measure
1	Front length (side neck point to hem)	1	Waistband depth CF
2	Centre back length	2	Waistband depth CB
3	Side length	3	Waistband depth side
4	Chest width (2.5cm down from underarm)	4	Waistband width front (measured straight at top edge)
5	Across chest (6.5cm down from centre neck seam)	5	Hip width (10cm down from top edge)
6	Across back (10cm down from centre neck seam)	6	Inseam (measured along seam, CF seam to hem)
7	Waist width (40cm down from shoulder high point)	7	Outseam/length (top edge to hem)
8	Bottom opening width (edge to edge, straight)	8	Front rise (top edge to crotch seam intersection, measured along curve)
9	Sleeve length top armhole (shoulder high point to sleeve opening)	9	Back rise (top edge to front seam, measured along curve)
10	Sleeve length underarm	10	Thigh width (5cm down from crotch)
11	Curved armhole width (front)	11	Knee width (½ of inseam length)
12	Sleeve width (2.5cm below armhole, parallel to sleeve opening)	12	Calf width (25cm up from bottom hem)
13	Elbow width (1/2 of underarm sleeve length)	13	Leg opening width (measured straight)
14	Sleeve opening width		
15	Neck depth front		
16	Neck drop front		
17	Neck drop back		
18	Neck width		
19	Neck base		



Appendix Figure M-1: Garment flat measurements on front of compression top

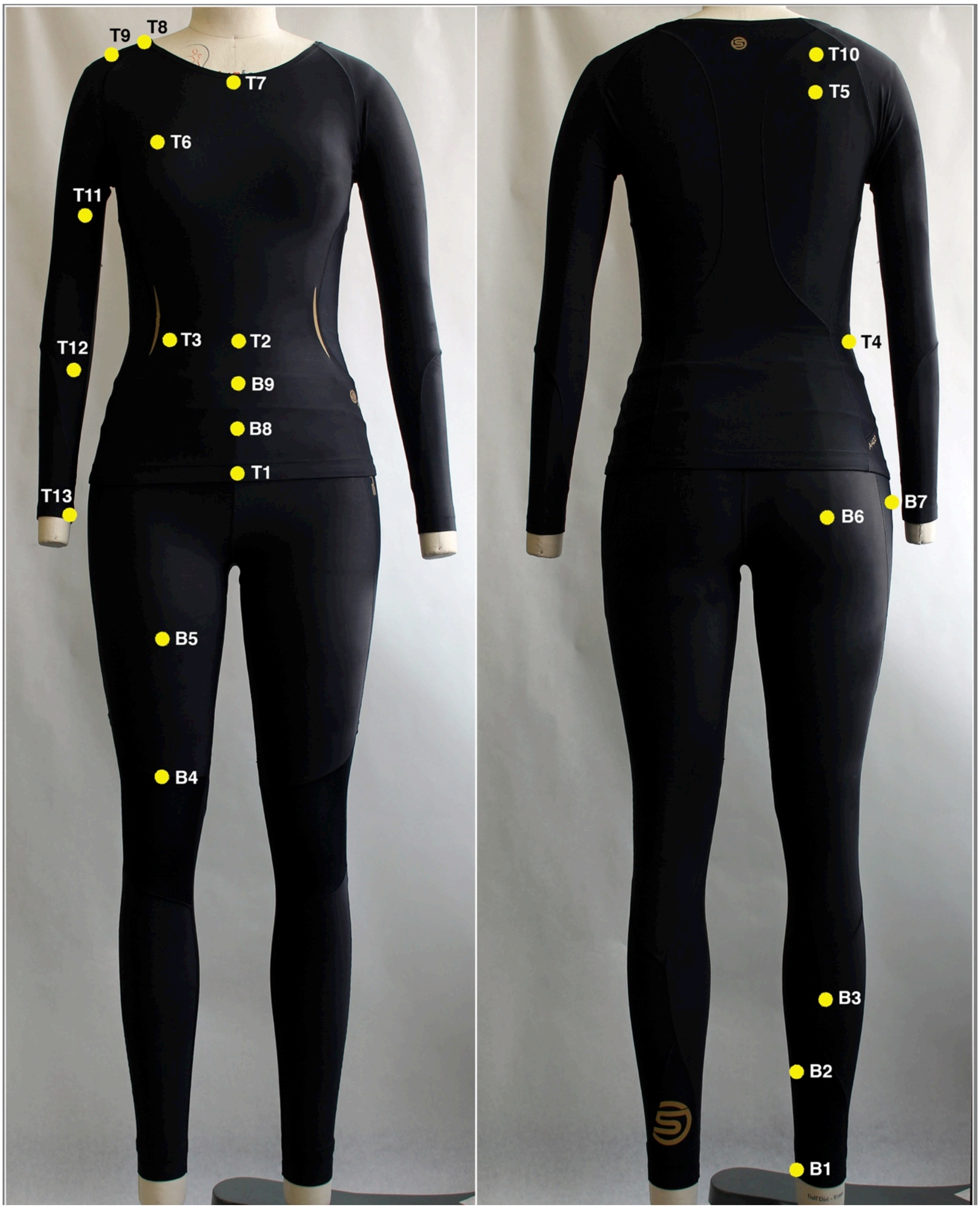


Appendix Figure M-2: Garment flat measurements on back of compression top



Appendix Figure M-3: Garment flat measurements on compression tights

Appendix N. Pressure measurement locations



Appendix Figure N-1: Selected pressure measurement locations shown on mannequin

Appendix Table N-1: Selected pressure measurement locations

Tights	Top
B1: Hem at inside leg	T1: Hem at centre front
B2: 12cm above inner ankle	T2: 5cm above navel
B3: Calf at maximum girth	T3: Front oblique (5cm up from navel, 10cm to side)
B4: 5cm above upper border of patella	T4: Waist at side
B5: Midway along thighbone	T5: Shoulder blade 10cm down from neckline
B6: Gluteus Maximus at greatest projection	T6: Front chest muscle at armpit height
B7: 5cm below waistband seam at side	T7: Neckline at centre front
B8: 10cm below navel at centre front	T8: Neckline at top of shoulder
B9: Waistband centre front	T9: Top of shoulder 5cm from neckline
	T10: 5cm down from shoulder at back
	T11: Inner biceps at maximum girth
	T12: Inner forearm at maximum girth
	T13: Sleeve hem at inner wrist

Appendix O. Sub Sports compression garments

a) b) c) d)

Appendix Figure O-1: Sub Sports RX Active Women's long sleeve compression top and long tights

Appendix Table O-1: Garment flat measurements of Sub Sports compression top

	Point of Measure - Top	Size M
1	Front length (side neck point to hem)	58.75
2	Centre back length	59.2
3	Side length	39.45
4	Chest width (2.5cm down from underarm)	36.05
5	Across chest (6.5cm down from centre neck seam)	32.1
6	Across back (10cm down from centre neck seam)	22
7	Waist width (40cm down from shoulder high point)	31.2
8	Bottom opening width (edge to edge, straight)	32.8
9	Sleeve length top armhole (shoulder high point to sleeve opening)	66.1
10	Sleeve length underarm	47.1
11	Curved armhole width	0
12	Sleeve width (2.5cm below armhole, parallel to sleeve opening)	14.3
13	Elbow width (1/2 of underarm sleeve length)	10.2
14	Sleeve opening width	7
15	Neck depth front	11.45
16	Neck drop front	13.65
17	Neck drop back	2.3
18	Neck width	13.5
19	Neck base	0

All measurements in cm

Appendix Table O-2: Garment flat measurements of Sub Sports compression tights

	Point of Measure - Tights	Size M
1	Waistband depth CF	3.45
2	Waistband depth CB	3.4
3	Waistband depth side	3.4
4	Waistband width front (measured straight at top edge)	26.25
5	Hip width (10cm down from top edge)	28.4
6	Inseam (measured along seam, CF seam to hem)	60.55
7	Outseam/length (top edge to hem)	80.95
8	Front rise (top edge to crotch seam intersection, measured along curve)	19.1
9	Back rise (top edge to front seam, measured along curve)	33.6
10	Thigh width (5cm down from crotch)	18.1
11	Knee width (½ of inseam length)	12.6
12	Calf width (25cm up from bottom hem)	12.9
13	Leg opening width (measured straight)	9.5

All measurements in cm

WOMEN'S SIZING

		XS	S	M	L	XL	XXL
SIZE	UK	6	8	10	12	14	16
	US	0-2	4-6	8-10	12-14	16	18
CHEST		29-32"	32-35"	35-38"	38-41"	41-44"	44-47"
		74-81cm	81-89cm	89-96cm	96-104cm	104-112cm	112-119cm
WAIST		24-26"	26-28"	28-30"	30-32"	32-34"	34-36"
		61-66cm	66-71cm	71-76cm	76-81cm	81-86cm	86-91cm

Appendix Figure O-2: Sub Sports size chart

Appendix P. Documentation developed for wearer trials

Wearer Trial – Step-by-Step Experimental Protocol

	Protocol	Resources Required
1	**Welcome and briefing**	
1.1	Welcome participant and introduce to staff	
1.2	Participant to read information sheet and ask questions	Information sheet
1.3	Participant to sign consent form	Consent form
2	**Body scan in underwear**	
2.1	Complete the subject records database	
2.2	Print and sign the consent form (technician and participant)	
2.3	Take manual measurements (height, weight, head circumference, min. hand circumference, hand length)	Tape measure
2.4	Take body scan	Hair ties
3	**Photographs**	
3.1	Participant to don compression garments	Compression garments, size chart
3.2	Take photographs of participant wearing compression garment	Camera
4	**Body scan in compression sportswear**	
4.1	Mark pressure measurement points	Tape, print out of measurement positions and table
4.2	Take body scan in colour	
5	**Questionnaire**	
5.1	Go through questionnaire with participant	Print out of questionnaire, pen, marker pen
6	**Pressure measurements**	
6.1	Place sensors underneath garment	Print out of measurement positions and table, Picopress sensors, tape
6.2	Measure pressure values twice in anatomic position and additional positions if needed.	Picopress device, measurement table
7	**Debrief and Feedback**	
7.1	Participant to change back into normal clothes	
7.2	Participant to provide feedback (if desired)	
7.3	Debrief and thanks	Body scan print out, refreshments

Appendix Figure P-1: Step-by-step experimental protocol for wearer trials

Appendix Figure P-2: Wearer trial recruitment poster

Manchester
Metropolitan
University

WEARER TRIAL INFORMATION SHEET

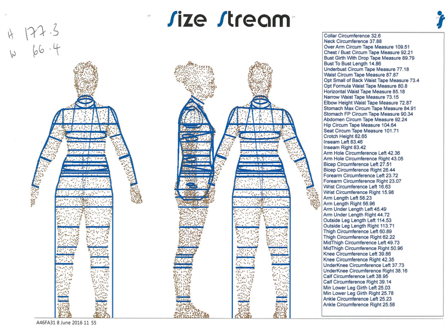
Researcher: Kristina Brubacher
Study Title: Designing Sports Compression Garments with Controlled Pressure: A Model for the Design Development of Women's Compression Garments
Institution: Manchester Fashion Institute, Faculty of Arts and Humanities, Manchester Metropolitan University
Date: January 2017

Thank you for considering to participate in this wearer trial and supporting the completion of this Doctoral study. The following information provides further details about the wearer trial.

What is the purpose of the wearer trial?
Previous research on compression sportswear at the Manchester Fashion Institute has demonstrated significant variations in compression forces for mid-range sized garments clothing a mannequin. This wearer trial seeks to map the pressures applied by commercial whole-body sports compression garments to recreational athletes' bodies across the range of core sizes. The findings will be used to define principles for achieving comparable compression across sizes, which will improve the functionality of compression sportswear.

What will the wearer trial involve?

- The process will be explained and consent forms will be completed.
- Your body measurements will be captured with a non-invasive and contactless 3D body scanner, which generates accurate body measurements and a personalised model.
- You will be asked to wear a long sleeve compression top and long compression tights. There will be a private changing area to get changed.
- A 3D scan of your body wearing the compression garments will be taken.
- Photographs will be taken to assess the fit of the garments. Please note that your face will not be recorded in the photographs.
- You will be asked a few questions about the compression garments you are wearing.
- The amount of pressure applied by the compression garments to your body will be measured using thin sensors, which will be placed between your body and the garments.
- At the end of the trial you will be provided with a print out of your individual scanned body model and measurements (similar to the picture on the right). You will also have the opportunity to provide feedback.




What will I need to wear?
To allow for accurate measurements, underwear should be close fitting. Please wear the type of underwear you would wear when exercising, i.e. briefs and a sports bra.

Where will the wearer trial take place?
The wearer trial will be held in the Righton Building at the MMU Manchester Campus. Please follow this link for directions and a campus map: http://www2.mmu.ac.uk/travel/manchester/

Are there any risks in taking part?
There are no anticipated risks to you if you take part in the study, nor are there likely to be any adverse effects. Your participation will be covered by the University's insurance scheme, as any study that has been approved by the Manchester Metropolitan University.

What are the benefits of taking part?
You get the opportunity to trial sports compression garments and to experience the latest technologies used to develop these. At the end of the session you will be given a 3D body model print out with your body's silhouette and accurate body measurements.

Will my participation be kept confidential, and what will happen to the results?
All information collected about you during the wearer trial will be kept confidential to comply with ethical considerations. Data will be coded so that there will be no direct connection between your identification and the data. You will not be identifiable in any publications arising from this study.

What will happen if I want to stop taking part?
In line with ethical governance at Manchester Metropolitan University, you are free to withdraw from the wearer trial at any time without giving any reason or explanation.

What happens next?
You are under no obligation to take part in this wearer trial; it is completely your choice. However, if you would like to take part, please email the researcher providing the following information:

- **Name:**
- **Email address:**
- **Age:**
- **Height:**
- **Weight:**
- **Chest circumference (if known, otherwise bra size):**
- **Type of sport you participate in:**
- **Training hours per week:**
- **Years of training at stated frequency:**

Once we have received this information, we will send you a link to an online doodle poll showing available appointment times. Please select a suitable appointment. You will receive a confirmation email with the exact details of where to meet on the day.

If you have any questions or require further information, please contact the researcher:
Kristina Brubacher
Manchester Fashion Institute, Faculty of Arts and Humanities, MMU
Telephone: 07784666371
Email: kristina.brubacher@stu.mmu.ac.uk

Wearer Trial Information Sheet 2

Appendix Figure P-3: Wearer trial participant information sheet

Appendix Figure P-4: Wearer trial recruitment flyer for second recruitment phase

Manchester Metropolitan University

Kristina Brubacher
Doctoral Researcher
Manchester Fashion Institute
Righton Building, Cavendish Street
Manchester Metropolitan University

Consent Form

Title of Project: Designing Sports Compression Garments with Controlled Pressure: A Model for the Design Development of Women's Compression Garments

Name of Researcher: Kristina Brubacher

Participant Identification Code for this project:

1. I confirm that I have read and understood the Participant Information Sheet for the above project and have had the opportunity to ask questions about the procedure of the wearer trial.

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason to the named researcher.

3. I understand that photographs will be taken during the wearer trial, but that my face will not be recorded or stored in the photographs.

4. I give permission for the body scan data captured of me during the wearer trial to be used by the named researcher in the context of this research project.

5. I understand that all data collected during the wearer trial will be stored and archived anonymised as part of this research project.

6. I agree to take part in the above research project.

Name of Participant	Date	Signature
Researcher	Date	Signature

To be signed and dated in presence of the participant

Appendix Figure P-5: Wearer trial consent form

Appendix Q. Body scanner validation study

The purpose of this small-scale validation study was to get an indication of the accuracy of the body measurements obtained through the use of the Size Stream SS14 body scanner (Size Stream, Cary, NC, USA). For this basic exercise, a female subject was first manually measured and then scanned. The subject was given a pair of long compression tights and a long sleeve compression top to wear during the 3D body scan and manual measurement process. The study protocol is listed below:

1. Subject to don whole-body compression garment (Elite RX Active Women's Long Sleeve Top and Elite RX Active Women's Leggings, Sub Sports, UK, size Medium).
2. Take photographs.
3. Take manual measurements with a calibrated tape measure (hoechstmass®, Germany) and mark landmarks with tape (on right side of body).
4. Take colour body scan of subject wearing compression garment with tape marks.

All measurements were taken with the subject breathing normally. The manual and automatic measurements were compared and percentage differences calculated. The limit of acceptable variations was set at ±5% to allow space for measurement errors.

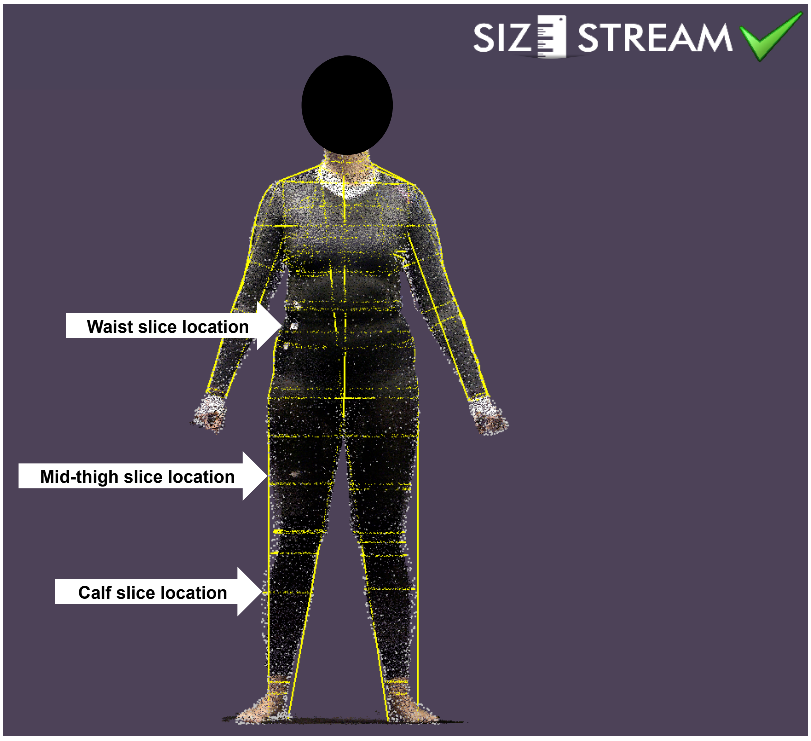
The test subject who participated in the validation study was a 38-year-old female volunteer (height: 176cm, weight: 75kg). She was informed about the process of the study and gave written, informed consent. There was a private changing cubicle for the subject to get changed into the compression garments. To have a record of the fit of the garments, photographs were taken from front, back and both side angles. The researcher marked the following body landmarks on the outside of the compression garments worn by the subject using tape following relevant standards (British Standards Institution, 2017b, 2017c):

- Ankle level
- Calf level

- Knee level
- Mid-thigh
- Hip level
- Waist level
- Shoulder point
- High neck point
- Biceps
- Elbow point
- Wrist point

The researcher manually measured selected body measurements following the standards used by Size Stream (refer Appendix R) and utilising the landmarks that had been marked on the outside of the CGs to identify the correct measurement locations. The subject was then scanned using the colour mode of the Size Stream 3D body scanner, so that the tape marks would be visible on the colour scan data. The scanning process followed the standard Manchester Fashion Institute scanning protocol. A technician was present at all times during the study.

The body scan data was later cleaned and analysed in the Size Stream Studio software. All movable body landmarks were checked for accuracy. The right shoulder point was located slightly too far inward and was thus moved slightly outwards. Automatic measurements were extracted from the cleaned scan file. The software’s slice tool was used to obtain circumference measurements at the locations where tape marks had been placed on the scan. However, not all tape marks were visible on the colour 3D body scan, so slices could only be taken at the waist, mid-thigh and calf (see Appendix Figure Q-1).



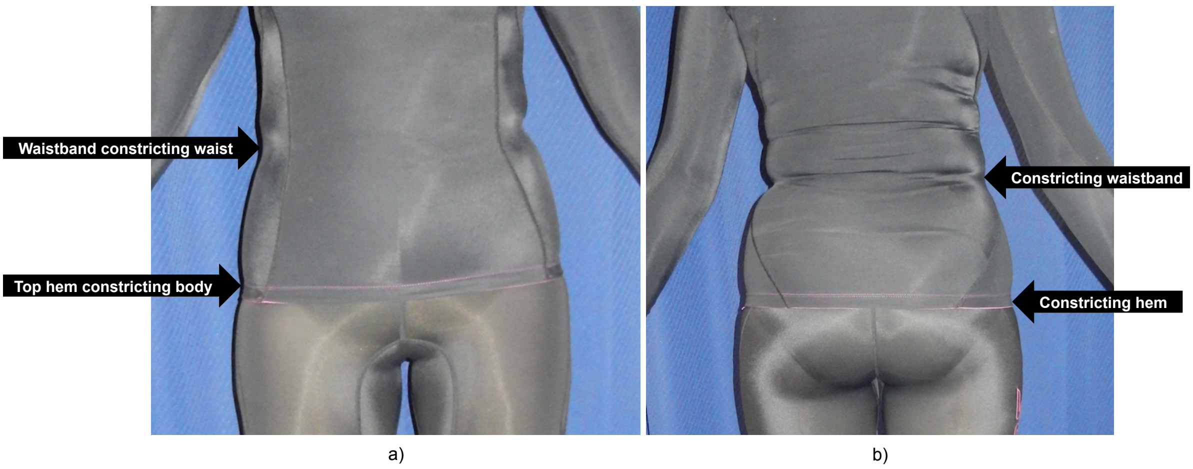
Appendix Figure Q-1: Slice locations on body scan

The results of the manual measurements, automatic measurements and slices are shown in Appendix Table Q-1 together with the calculated differences. All circumference measurements obtained from the body scanner are slightly larger than the manual measurements. However, only the waist and shoulder length measurements vary more than ±5%. Waist height is difficult to accurately identify. The waist was identified as the mid point between the lowest rib bone and the top of the hipbone. However, the compression tights were slightly tight at the waist and thus affected the contour of the waist as can be seen in Appendix Figure Q-2. This made it difficult to accurately measure the waist, explaining the manual and scanner measurements.

Initial test scans with the Size Stream SS14 body scanner had already unearthed a problem with the shoulder length measurements in most scans captured using the scanner. Even though the shoulder landmark was moved to a more appropriate location, there was still a problem with the measurement. It was concluded that overall the measurements obtained from the body scanner were acceptable for this study as shoulder length measurements were not the most important measurements for this study. It was planned to carefully scrutinise the shoulder landmarks and corresponding measurements on all future body scans.

Appendix Table Q-1: Results of body scanner validation

Measurement (cm)	Manual	Scanner		Manual - Automatic		Manual - Slice
		Automatic	Slice tool	Difference (cm)	Difference (%)	Difference (%)
Ankle circumference	25.3	25.95	-	-0.65	-2.50	-
Calf circumference	40.9	42.32	42.61	-1.42	-3.36	-4.01
Knee circumference	41.3	43.21	-	-1.91	-4.42	-
Mid-thigh circumference	54.9	54.02	55.87	0.88	1.63	-1.74
Crotch height	82.3	81.74	-	0.56	0.69	-
Hip circumference	101.7	105.66	-	-3.96	-3.75	-
Waist circumference	80.4	94.71	92.1	-14.31	**-15.11**	**-12.70**
Under bust circumference	82.9	84.91	-	-2.01	-2.37	-
Chest circumference	96.3	97.87	-	-1.57	-1.60	-
Shoulder length	12.3	13.53	-	-1.23	**-9.09**	-
Biceps circumference	30	31.37	-	-1.37	-4.37	-
Elbow girth	26.9	28.12	-	-1.22	-4.34	-
Wrist circumference	16.9	17.14	-	-0.24	-1.40	-
		Overall mean percentage difference:			-3.85	



Appendix Figure Q-2: Hems of compression garments constricting wearer's midsection; a) front view; b) back view

Appendix R. Selected Size Stream 3D body scan measurements and applied measurement standards

Appendix Table R-1: Applied measurement standards for automatic measurements of Size Stream 3D body scanner

Size Stream Automatic Measurements	ISO 7250	ISO 8559
Across Back Tape Measurement		2.1.6
Ankle Circumference L&R		2.1.24
Ankle Height L&R (use landmarks)		2.2.7
Arm Hole Circumference L&R		2.2.20
Arm Length L&R		2.2.22
Arm Under Length L&R		2.2.24
Back Shoulder Width		2.1.5
Bicep Circumference L&R		2.1.13
Body Depth (use landmarks)	4.1.10	
Bust Level Depth (use landmarks)	4.2.16	
Calf Circumference L&R	4.4.13	2.1.22
Chest Circumference Tape Measure		2.1.8
Crotch Height	4.1.7	2.2.27
Elbow Girth		2.1.14
Forearm Circumference L&R	Largest girth of the lower arm.	
Hip Circumference Tape Measure		2.1.12
Hip Height (use landmarks)	4.1.6	2.2.4
Inseam L&R	Length from the crotch point down the leg to the floor	
Knee Circumference L&R		2.1.20
Knee Height R&L (use landmarks)	4.1.8	2.2.6
Mid-Thigh Circumference L&R		2.1.19
Min Lower Leg Girth L&R		2.1.23
Neck Circumference		2.1.3
Outside Leg Length L&R		2.2.25
Seat Circumference Tape Measure	Horizontal circumference at the most prominent rear point between the waist and crotch.	
Seat Height (use landmarks)		2.2.4
Shoulder Length L&R		2.1.4
Shoulder Slope L&R		2.3.1
Shoulder Width		2.1.5
Sleeve Length L&R		2.2.23
Thigh Circumference L&R	4.4.12	2.1.18
Thigh Length		2.2.26
Trunk Length (use landmarks)		2.2.2
Under Bust Circumference Tape Measure		2.1.10
Under Knee Circumference L&R		2.1.21

Size Stream Automatic Measurements	ISO 7250	ISO 8559
Under Knee Height L&R	Height from the floor to the Under Knee Circumference.	
Waist Circumference Tape Measure		2.1.11
Waist Height		2.2.3
Wrist Circumference L&R	4.4.11	2.1.15

Appendix S. Steps of body scanning protocol

The following steps were adhered to by the researcher and technician when scanning participants:

1. After signing the consent form, the participant was given a tour of the body scanner and instructed on the specifics of the body scanning procedure.
2. The participant went into the private changing cubicle to undress up to her underwear and donned the dressing gown provided. She was told to wear a sports bra or the type of bra that she would usually wear when exercising. If she was not already wearing her sports bra, she changed into the bra prior to donning the dressing gown. Participants were also asked to remove bracelets, watches and large rings at this point.
3. Five manual measurements were taken before the scan: the height, weight, head circumference, smallest hand circumference and hand length. The participant was asked to stand erect on the base of the height measure with heels, buttocks and shoulders against the wall. Arms were hanging naturally on the sides of the body and the head facing forward. The height measurement was read from the height measure. The participant was then directed to stand in the centre of the platform of the calibrated electronic scales and 1kg was subtracted from the weight for the gown before the weight was recorded. The circumference measuring tape was used to measure the participant's head circumference by placing it around the head over the occipital bone at the back and above the ears. The participant was then asked to minimise the circumference of her hand as much as possible as if she was trying to put on a bracelet. The circumference tape measure was placed above the thumb knuckle and the circumference measurement was recorded. The hand length was measured from the wrist crest to the tip of the middle finger.
4. The participant was given hair accessories to arrange her hair in a manner that would ensure that the neck and shoulder areas were clear from hair. This was necessary since the 3D body scanner is a surface scanner that would otherwise incorporate the hair into the neck contour.

5. The participant was shown the exact scanning position to be taken. The participant was then asked to step into the scanner and the privacy curtain was fully closed. The participant was instructed to take off the dressing gown and glasses (if wearing any) and to place these outside the scanning area. The participant stood on the footprints marked on the floor at approximately shoulder-width apart and grasped the handholds located at either side of the body to enter the instructed scanning position. The participant informed the researcher and technician when she was in scanning position ready to be scanned.
6. The scan was commenced via the scanner software on a computer that was solely used for body scanning purposes and was password protected. Scanning instruction telling the participant to keep as still as possible whilst the scan was being taken sounded from the scanner by an automated voice recording.
7. The researcher and technician checked the refined body mesh and extracted measurements of the scan in the scanning software on the computer screen to ensure that the data was complete and of good quality, whilst the participant was told to relax and wait in the scanning cubicle. If the scanning data was not complete or of good quality, the scan was repeated. Once the scan was approved, the participant was told to don the dressing gown and step out of the scanning cubicle.

Appendix T. Results of normality test of anthropometric data

For or $p < 0.05$: distribution is significantly different from a normal distribution (i.e. it is non-normal) (Field, 2013) (highlighted in grey).

Appendix Table T-1: Test for normal distribution of anthropometric data for all participants (*N* = 33)

	Shapiro-Wilk		
	Statistic	***df***	***p***
Height	.976	33	.667
Weight	.921	33	.019
BMI	.977	33	.701
Chest circumference	.921	33	.020
Under bust circumference	.955	33	.191
Waist circumference	.958	33	.234
Hip circumference	.982	33	.845
Seat circumference	.975	33	.621
Inseam right	.986	33	.932
Biceps circumference right	.955	33	.182
Forearm circumference right	.980	33	.797
Wrist circumference right	.968	33	.432
Arm length right	.927	33	.029
Mid-thigh circumference right	.963	33	.304
Knee circumference right	.943	33	.083
Calf circumference right	.977	33	.677
Ankle circumference right	.972	33	.540

Appendix Table T-2: Test for normal distribution of anthropometric data for compression tights (*n* = 30)

	Shapiro-Wilk		
	Statistic	***df***	***p***
Height	.970	30	.542
Weight	.877	30	.002
BMI	.960	30	.304
Chest circumference	.927	30	.041
Under bust circumference	.938	30	.080
Waist circumference	.920	30	.027
Hip circumference	.973	30	.625
Seat circumference	.982	30	.879
Inseam right	.981	30	.844
Biceps circumference right	.958	30	.278
Forearm circumference right	.979	30	.792
Wrist circumference right	.965	30	.408

	Shapiro-Wilk		
	Statistic	*df*	*p*
Arm length right	.929	30	.045
Mid-thigh circumference right	.938	30	.080
Knee circumference right	.947	30	.143
Calf circumference right	.990	30	.990
Ankle circumference right	.978	30	.764

Appendix Table T-3: Test for normal distribution of anthropometric data for compression top (*n* = 31)

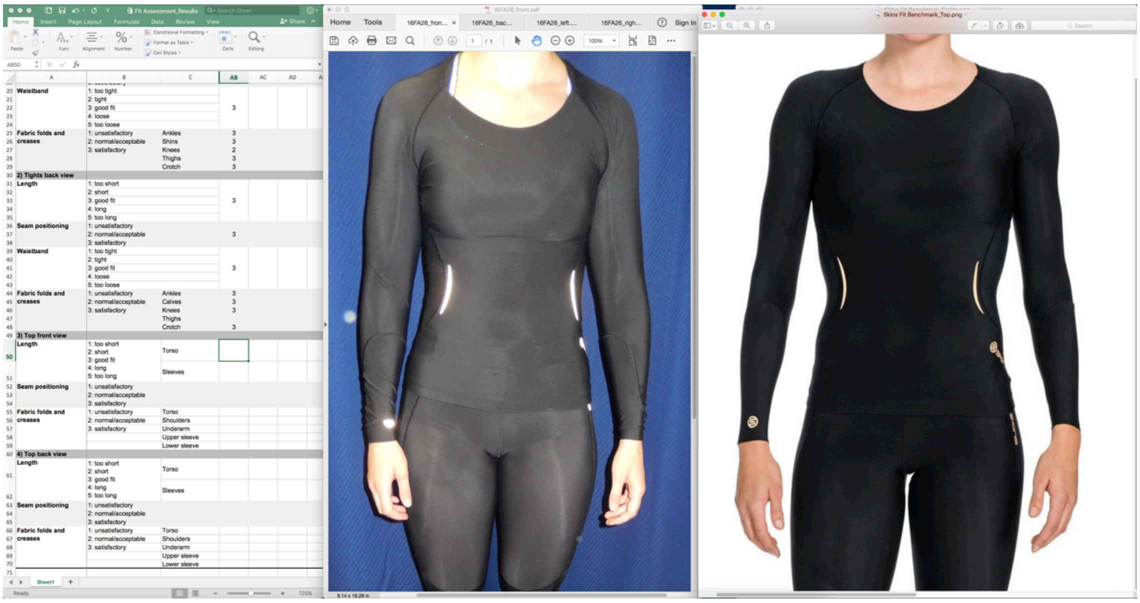
	Shapiro-Wilk		
	Statistic	*df*	*p*
Height	.979	31	.778
Weight	.916	31	.018
BMI	.977	31	.737
Chest circumference	.951	31	.162
Under bust circumference	.962	31	.322
Waist circumference	.940	31	.084
Hip circumference	.981	31	.837
Seat circumference	.973	31	.592
Inseam right	.985	31	.930
Biceps circumference right	.960	31	.298
Forearm circumference right	.984	31	.913
Wrist circumference right	.969	31	.487
Arm length right	.928	31	.039
Mid-thigh circumference right	.955	31	.213
Knee circumference right	.920	31	.023
Calf circumference right	.974	31	.632
Ankle circumference right	.966	31	.420

Appendix U. Developed fit assessment system

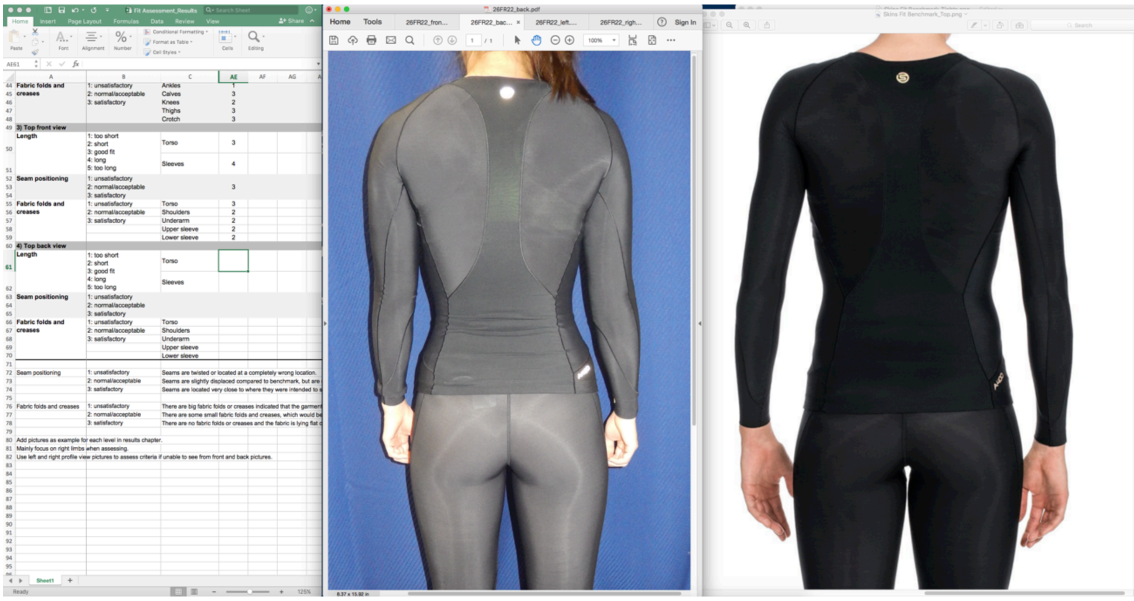
Appendix Table U-1: Fit assessment scoring sheet

Fit Assessment		
1) Tights front view		
Length		1: too short 2: short 3: good fit 4: long 5: too long
Seam positioning		1: unsatisfactory 2: normal 3: satisfactory
Waistband		1: too tight 2: tight 3: good fit 4: loose 5: too loose
Fabric folds and creases		
	Ankles	1: unsatisfactory 2: normal 3: satisfactory
	Shins	
	Knees	
	Thighs	
	Crotch	
2) Tights back view		
Length		1: too short 2: short 3: good fit 4: long 5: too long
Seam positioning		1: unsatisfactory 2: normal 3: satisfactory
Waistband		1: too tight 2: tight 3: good fit 4: loose 5: too loose
Fabric folds and creases		
	Ankles	1: unsatisfactory 2: normal 3: satisfactory
	Calves	
	Knees	
	Thighs	

	Crotch	
3) Top front view		
Length		1: too short 2: short 3: good fit 4: long 5: too long
	Torso	
	Sleeves	
Seam positioning		1: unsatisfactory 2: normal 3: satisfactory
Fabric folds and creases		
	Torso	1: unsatisfactory 2: normal 3: satisfactory
	Shoulders	
	Underarm	
	Upper sleeve	
	Lower sleeve	
4) Top back view		
Length		1: too short 2: short 3: good fit 4: long 5: too long
	Torso	
	Sleeves	
Seam positioning		1: unsatisfactory 2: normal 3: satisfactory
Fabric folds and creases		
	Torso	1: unsatisfactory 2: normal 3: satisfactory
	Shoulders	
	Underarm	
	Upper sleeve	
	Lower sleeve	



Appendix Figure U-1: Fit assessment on computer screen: front view



Appendix Figure U-2: Fit assessment on computer screen: back view

Appendix V. Questions generated for wearer trial questionnaire

Comfort

- Do you feel comfortable wearing the garment? – A great deal, quite a bit, somewhat, very little, not at all
- Do you experience discomfort whilst wearing the garment?
- The amount of compression is… 1: far too much, 2: too much, 3: just right, 4: too little, 5: far too little (Hooper et al., 2015)
- Were you relieved to take the garment off after the trial?
- Was the garment comfortable close to your skin?
- Were you able to move freely whilst wearing the garment?/ Did the garment allow you to move freely?
- Did you feel restricted whilst wearing the garment?
- Was the garment easy to don?
- Was the garment easy to doff?

Aesthetics

- How would you rate the following garment aspects?
- Overall shape
- Garment length
- Garment design/style
- Garment colour
- Finish of the fabric
- Handfeel of the garment
- Shape of the neckline
- Shape of the armholes
- The garment is attractive in appearance.
- The garment conceals the body well.
- The garment supports my muscles.

Fit

- How do you rate the overall fit of the tights?
- How do you rate the overall fit of the top?
- Do you prefer wearing close-fitting garments during exercise?
- How important is garment fit to you?
- Do you expect a close-fitting garment to feel like a second skin?
- Did the top feel too tight? If yes, at what part of your body?
- Did the tights feel too tight? If yes, at what part of your body?
- The garment fits my body shape well.

Perception of garment

- Do the compression tights fulfil your needs for exercising tights? If no, how would you adjust the tights?
- Does the top fulfil your needs for an exercising top? If no, how would you adjust the top?
- Would you wear this particular compression top during your usual exercise?
- Would you wear these particular compression tights during your usual exercise?
- How did you feel when wearing the garment?
- How enjoyable was wearing the garment?
- How would you rate the overall quality of the garment?
- The garment has a good surface texture.
- Do you feel any of the following when wearing the garments?
    - Smoothness
    - Softness
    - Coarseness
    - Warmth
    - Stiffness
    - Clammy
    - Sticky
    - Heavy
    - Prickly

  - Scratchy

Perception of the garment improving performance

- How did the garment make you feel whilst wearing it?
- Do you prefer wearing additional clothing over compression garments?
- Do you believe that these compression garments could improve your performance?
- Do you believe that these compression garments could improve your recovery?

Open-ended questions

- My main concern with these garments is…
- I especially like about these garments that…
- Any other comments…

Appendix W. Final wearer trial questionnaire

Wearer Trial Questionnaire

Date:

Participant:

1) Overall, do you feel comfortable wearing the compression garments?

1	2	3	4	5
Totally uncomfortable				Completely comfortable

2) Do the compression garments induce any discomfort?

1	2
Yes	No

If YES:

2a) How would you rate the level of discomfort?

1	2	3	4	5
Slight discomfort				High level of discomfort

2b) Please indicate the areas where you feel discomfort.

1

3) How would you rate the level of compression of the top?

1	2	3	4	5
Far too much	Too much	Just right	Too little	Far too little

4) How would you rate the level of compression of the tights?

1	2	3	4	5
Far too much	Too much	Just right	Too little	Far too little

If 1, 2, 4 or 5 in questions 3 and/or 4:

4a) Please indicate the areas on your body where compression feels too tight or too little.

5) How would you rate the degree to which the compression garments allow you to move freely?
(Ask participant to lift arms, arms to side, crossing in front of chest, bend knee and lift leg, bend forward trying to touch toes)

1	2	3	4	5
Very much restricted in movement				Able to move freely without restrictions

2

If 1 or 2:

5a) At what parts of your body does the garment restrict movement?

6) How do you rate the overall fit of the compression top?

1	2	3	4	5
Poor				Excellent

7) How do you rate the overall fit of the compression tights?

1	2	3	4	5
Poor				Excellent

If 1 or 2 in question 6 and/or 7:

7a) Please indicate at what parts of your body the compression garments fit badly.

3

8) How would you rate the next-to-skin feel of the compression garments?

1	2	3	4	5
Poor				Excellent

9) How would you rate the design/style of the compression garments?

1	2	3	4	5
Poor				Excellent

10) Would you wear this particular compression top during your usual exercise?

1	2
Yes	No

If NO:

10a) Why not?

11) Would you wear these particular compression tights during your usual exercise?

1	2
Yes	No

If NO:

11a) Why not?

12) Do you prefer wearing additional clothing over compression garments?

1	2
Yes	No

13) Do you believe that these compression garments could improve your performance?

1	2
Yes	No

14) Do you believe that these compression garments could improve your recovery?

1	2
Yes	No

15) How often do you usually wear sports compression garments during exercise?

1	2	3	4	5
Never	Rarely	Sometimes	Frequently	Always

16) How often do you usually wear sports compression garments during recovery?

1	2	3	4	5
Never	Rarely	Sometimes	Frequently	Always

17) Is there anything that you particularly like or dislike about the compression garments that you are wearing? If so, what is it?

5

Appendix Figure W-1: Wearer trial questionnaire form

Appendix X. Pressure measurement postures

a) b) c) d)

Appendix Figure X-1: Pressure measurement postures used in wearer trials: a) Posture 1; b) Posture 2; c) Posture 3; d) Posture 4

Appendix Y. Results of normality test of pressure data

For or $p < 0.05$: distribution is significantly different from a normal distribution (i.e. it is non-normal) (Field, 2013) (highlighted in grey).

Appendix Table Y-1: Test for normal distribution of in vivo pressure for compression tights

	Shapiro-Wilk		
	Statistic	*df*	*p*
B11	.959	33	.246
B21	.947	33	.109
B22	.953	33	.165
B23	.943	33	.086
B31	.734	33	.000
B32	.844	33	.000
B33	.947	33	.108
B41	.877	33	.001
B42	.938	33	.058
B43	.946	33	.105
B51	.925	33	.025
B52	.930	33	.034
B53	.935	33	.050
B61	.919	33	.017
B62	.936	33	.051
B63	.915	33	.014
B71	.953	33	.164
B81	.755	33	.000
B91	.963	33	.307

Appendix Table Y-2: Test for normal distribution of in vivo pressure for compression top

	Shapiro-Wilk		
	Statistic	*df*	*p*
T11	.957	33	.219
T21	.827	33	.000
T31	.806	33	.000
T41	.808	33	.000
T51	.777	33	.000
T54	.916	33	.015
T61	.859	33	.001
T64	.608	33	.000
T71	.623	33	.000
T81	.936	33	.051
T91	.954	33	.169
T101	.918	33	.016
T111	.938	33	.061
T114	.687	33	.000
T121	.946	33	.105
T124	.899	33	.005
T131	.947	33	.112

Appendix Z. Optitex Fabric Testing Unit

The Optitex Fabric Testing Unit (FTU) identifies the four fabric parameters required for the Optitex algorithm (Optitex, 2016:3):

- **Stretch:** The resistance of the cloth to stretching forces in the Warp (X) and the Weft (Y) directions affecting elasticity of the fabric. High stretch for lower elasticity. Bounds: 10-100,000
- **Shear**: The resistance of the cloth to shearing forces influence is on the diagonal direction of the fiber/ cloth. Bounds 10-20,000
- **Friction**: The resistance of cloth to its motion on the body's surface affects the way the cloth slides on the body. Bounds 0-1.
- **Bending**: The resistance of the cloth to bending forces affects the rigidity of the fabric. High bending for stiffer materials. Bounds: 0-1,000,000.

The FTU hardware has two separate configurations; one for friction and bending, where the fabric stays stationary, and one for stretch and shear where the fabric is moved (Optitex, 2009). The FTU integrates with a software programme called Fabric Center enabling the measurement of fabric parameters through the Fabric Center interface. The following four samples are required for testing (Optitex, 2016:13):

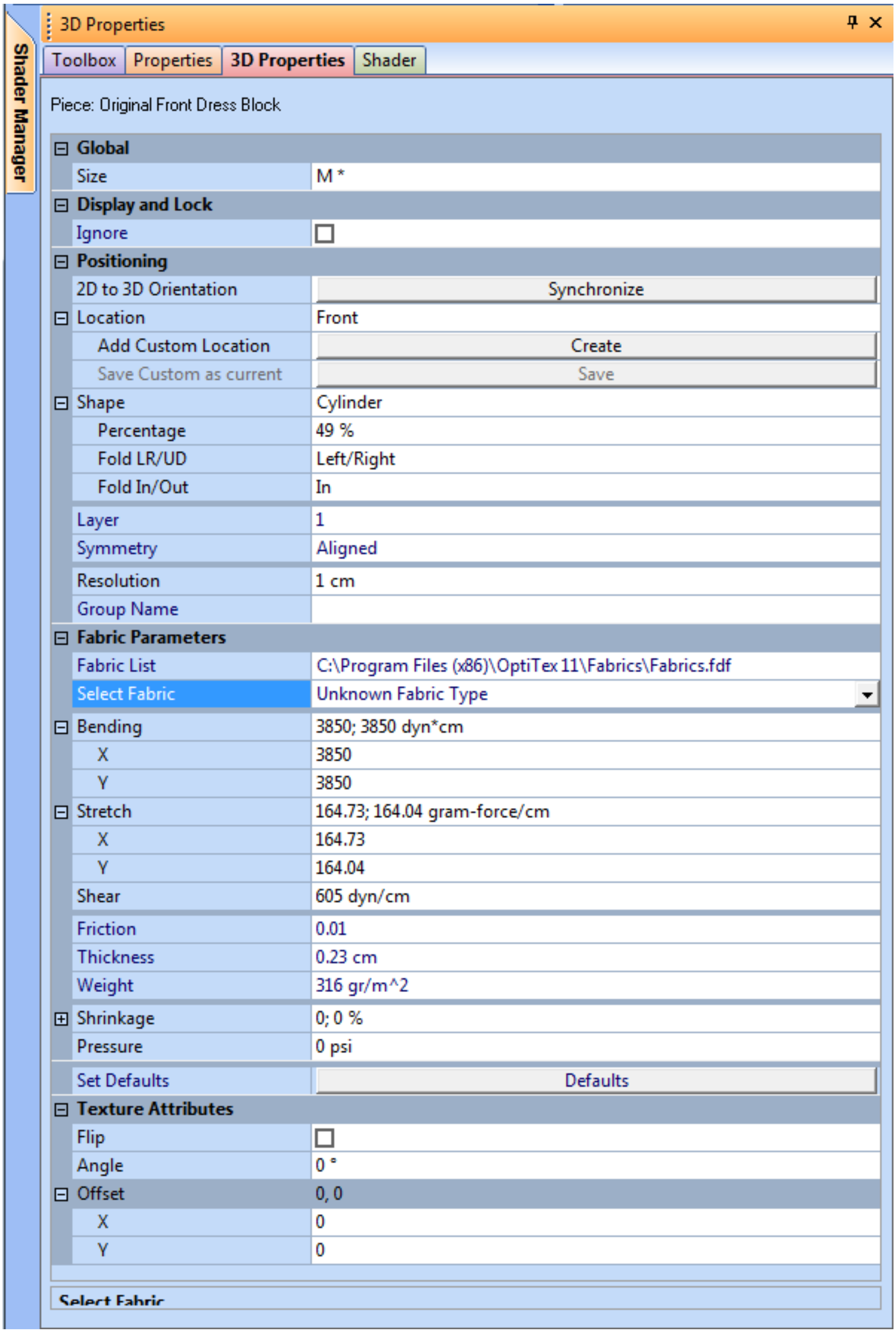
- Friction: 10x15 cm with grainline parallel to the longest edge.
- Bend and Stretch X: 3x10 cm with grainline parallel to the shortest edge.
- Bend and Stretch Y: 3x10 cm with grainline parallel to the longest edge.
- Shear: 3x10 cm with grainline at a 45-degree angle.

The FTU has an automated repeat function to validate measurements. The testing procedures are described in Appendix Table Z-1.

Appendix Table Z-1: Optitex Fabric Tests (Optitex, 2009)

Optitex Fabric Testing Unit – Test Procedures	
Bending test	Cut a piece of the fabric (pay attention to the weft direction), place the fabric on the surface outlined with the ruler, and start moving the fabric until part of the fabric is hanging in the air. Once the hanging portion reaches the bottom piece, also lined with a ruler, measure the distance of the fabric. We are looking for the bending value of the fabric based on its own weight.
Friction test (μ)	Cut a piece of the woven (detail the weft direction), and place it on the special platform, and over it, you place a weight equipped with a sensor. Raise the platform at a regular speed, and once the weight starts to slide on the fabric, the platform stops. The moment the weight started to move is the moment differentiating between the static friction value and the dynamic friction value. Reading the electronic meter allows you to calculate the sliding angle to find the final friction value.
Stretch test	We are looking for a number measured in units of grf*cm, which defines the relative force different fabrics have both in the x-axis and in the y-axis. For this, prepare two pieces of fabric – one cut on the weft and one on the warp. Place one of the pieces between the holder on the cart without stretching the fabric. Reset the meter and the weight. Start moving the cart to a defined distance and will the number on the weight. Because the fabric's resistance to stretching is not linear, measure the fabric's resistance at three distances to find the average, which will ensure better accuracy. Once you have finished with one piece, repeat the test with the second piece.
Shear test	We are looking for a number measured in grf*cm units, which defines the relative force the knit for a cutting movement (forces going in opposite directions) of the fabric. Cut a piece of fabric so the weft thread is at a 45-degree angle. Place the fabric on the cart crosswise and reset the meter and the weight. Start the machine, move the cart to a defined distance and read the weight.

Appendix AA. 3D properties in Optitex



Appendix Figure AA-1: 3D properties window in Optitex (screenshot)

Appendix BB. Training status of survey respondents

Appendix Table BB-1: Training Status of Survey Respondents

Training hours per week	**≤ 5**	**6-8**	**9+**			
Count	60	45	40			
Percentage (%)	41.4	31	27.6			
Years of experience	**≤ 2**	**3-4**	**5-10**	**11+**		
Count	50	36	31	28		
Percentage (%)	34.5	24.8	21.4	19.3		
Competitions in past 12 months	**≤ 5**	**6-10**	**11-20**	**21+**		
Count	47	30	41	27		
Percentage (%)	32.4	20.7	28.3	18.6		
Level of competition	**Recreational**	**Club**	**Regional**	**National**	**International**	**Not competing**
Count	22	78	18	15	9	3
Percentage (%)	15.2	53.8	12.4	10.3	6.2	2.1

Appendix CC. Crosstabulation of garment types and gender

Appendix Table CC-1: Crosstabulation of types of SCGs and gender

			What is your gender?		Total
			Male	Female	
What type of CGs do you usually wear?[a]	Long sleeve top	Count	29	13	42
		% within SCG_type	69.0%	31.0%	
		% within Gender	30.9%	25.5%	
	Short sleeve top	Count	20	4	24
		% within SCG_type	83.3%	16.7%	
		% within Gender	21.3%	7.8%	
	Tank top	Count	5	3	8
		% within SCG_type	62.5%	37.5%	
		% within Gender	5.3%	5.9%	
	Crop top/bra	Count	0	6	6
		% within SCG_type	0.0%	100.0%	
		% within Gender	0.0%	11.8%	
	Long tights	Count	35	29	64
		% within SCG_type	54.7%	45.3%	
		% within Gender	37.2%	56.9%	
	3/4 tights	Count	5	17	22
		% within SCG_type	22.7%	77.3%	
		% within Gender	5.3%	33.3%	
	Shorts	Count	41	19	60
		% within SCG_type	68.3%	31.7%	
		% within Gender	43.6%	37.3%	
	Body suit long	Count	0	1	1
		% within SCG_type	0.0%	100.0%	

			What is your gender?		Total
			Male	Female	
		% within Gender	0.0%	2.0%	
	Body suit short	Count	2	0	2
		% within SCG_type	100.0%	0.0%	
		% within Gender	2.1%	0.0%	
	Arm sleeves	Count	3	2	5
		% within SCG_type	60.0%	40.0%	
		% within Gender	3.2%	3.9%	
	Leg sleeves	Count	15	11	26
		% within SCG_type	57.7%	42.3%	
		% within Gender	16.0%	21.6%	
	Socks	Count	46	29	75
		% within SCG_type	61.3%	38.7%	
		% within Gender	48.9%	56.9%	
	Calf sleeve	Count	6	1	7
		% within SCG_type	85.7%	14.3%	
		% within Gender	6.4%	2.0%	
Total		Count	94	51	145

Note: Percentages and totals are based on respondents.

Appendix DD. Reliability statistics for attitude scale in main study

Appendix Table DD-1: Cronbach's alpha for attitude scale in main study

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N
0.842	0.845	12

Appendix Table DD-2: Inter-item correlation matrix for attitude scale in main study

	I feel more confident when wearing compression garments.	I feel more comfortable with my body when wearing compression garments.	Wearing compression garments improves my performance.	Wearing compression garments shortens my recovery time.	I achieve my goals faster when wearing compression garments.	Compression garments allow me to achieve my greatest potential.	I have a stronger belief in myself when wearing compression garments.	I don't need compression garments to achieve my athletic aims.	Wearing compression garments doesn't improve my ability as an athlete.	I feel restricted when wearing compression garments.	The promotional claims of compression garment brands are deceptive.	The beneficial effects of compression garments are overrated.
I feel more confident when wearing compression garments.	1.000	0.528	0.378	0.223	0.380	0.338	0.611	0.286	0.301	0.163	0.307	0.338
I feel more comfortable with my body when wearing compression garments.	0.528	1.000	0.165	0.085	0.248	0.242	0.464	0.034	0.084	0.361	0.138	0.173
Wearing compression garments improves my performance.	0.378	0.165	1.000	0.275	0.534	0.569	0.440	0.448	0.630	0.163	0.326	0.334
Wearing compression garments shortens my recovery time.	0.223	0.085	0.275	1.000	0.220	0.219	0.221	0.200	0.209	0.231	0.169	0.311
I achieve my goals faster when wearing compression garments.	0.380	0.248	0.534	0.220	1.000	0.551	0.515	0.349	0.406	0.240	0.298	0.473

	I feel more confident when wearing compression garments.	I feel more comfortable with my body when wearing compression garments.	Wearing compression garments improves my performance.	Wearing compression garments shortens my recovery time.	I achieve my goals faster when wearing compression garments.	Compression garments allow me to achieve my greatest potential.	I have a stronger belief in myself when wearing compression garments.	I don't need compression garments to achieve my athletic aims.	Wearing compression garments doesn't improve my ability as an athlete.	I feel restricted when wearing compression garments.	The promotional claims of compression garment brands are deceptive.	The beneficial effects of compression garments are overrated.
Compression garments allow me to achieve my greatest potential.	0.338	0.242	0.569	0.219	0.551	1.000	0.478	0.323	0.566	0.131	0.345	0.401
I have a stronger belief in myself when wearing compression garments.	0.611	0.464	0.440	0.221	0.515	0.478	1.000	0.326	0.401	0.242	0.310	0.285
I don't need compression garments to achieve my athletic aims.	0.286	0.034	0.448	0.200	0.349	0.323	0.326	1.000	0.545	0.065	0.160	0.287
Wearing compression garments doesn't improve my ability as an athlete.	0.301	0.084	0.630	0.209	0.406	0.566	0.401	0.545	1.000	0.108	0.198	0.271
I feel restricted when wearing compression garments.	0.163	0.361	0.163	0.231	0.240	0.131	0.242	0.065	0.108	1.000	0.208	0.266
The promotional claims of compression garment brands are deceptive.	0.307	0.138	0.326	0.169	0.298	0.345	0.310	0.160	0.198	0.208	1.000	0.573
The beneficial effects of compression garments are overrated.	0.338	0.173	0.334	0.311	0.473	0.401	0.285	0.287	0.271	0.266	0.573	1.000

Appendix Table DD-3: Summary of inter-item correlations for attitude scale in main study

	Mean	Minimum	Maximum	Range	Max./Min.	Variance	N
Inter-Item Correlations	0.313	0.034	0.630	0.597	18.805	0.021	12

Appendix Table DD-4: Item-total statistics for attitude scale in main study

Attitude Statement	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
I feel more confident when wearing compression garments.	35.50	36.127	0.581	0.510	0.825
I feel more comfortable with my body when wearing compression garments.	35.78	37.729	0.365	0.424	0.842
Wearing compression garments improves my performance.	36.11	35.252	0.645	0.542	0.820
Wearing compression garments shortens my recovery time.	35.71	38.832	0.343	0.169	0.841
I achieve my goals faster when wearing compression garments.	36.39	36.461	0.635	0.492	0.822
Compression garments allow me to achieve my greatest potential.	36.23	36.413	0.628	0.514	0.823
I have a stronger belief in myself when wearing compression garments.	36.00	34.681	0.649	0.540	0.819
I don’t need compression garments to achieve my athletic aims.	36.47	36.529	0.448	0.359	0.836
Wearing compression garments doesn’t improve my ability as an athlete.	36.51	35.099	0.556	0.547	0.827
I feel restricted when wearing compression garments.	35.47	38.459	0.312	0.233	0.845
The promotional claims of compression garment brands are deceptive.	36.51	38.113	0.441	0.390	0.835
The beneficial effects of compression garments are overrated.	36.19	36.324	0.541	0.490	0.828

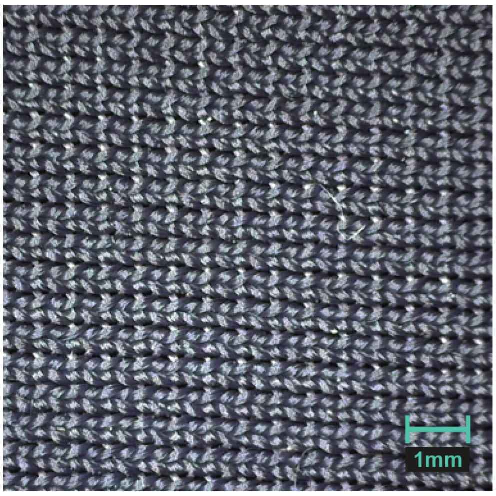
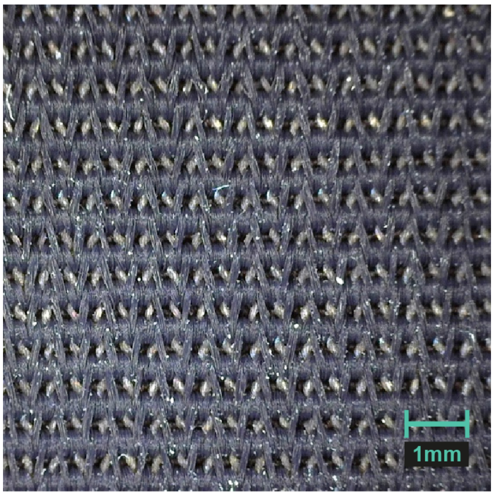
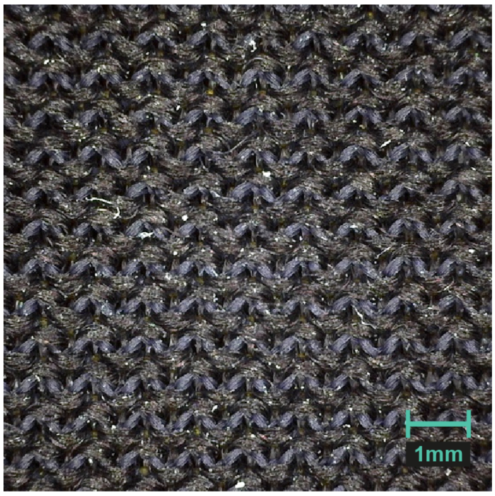
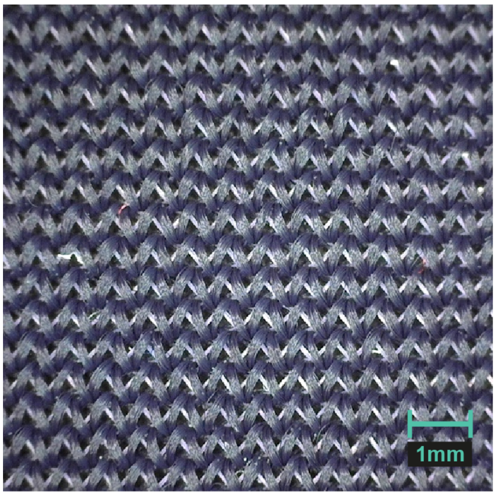
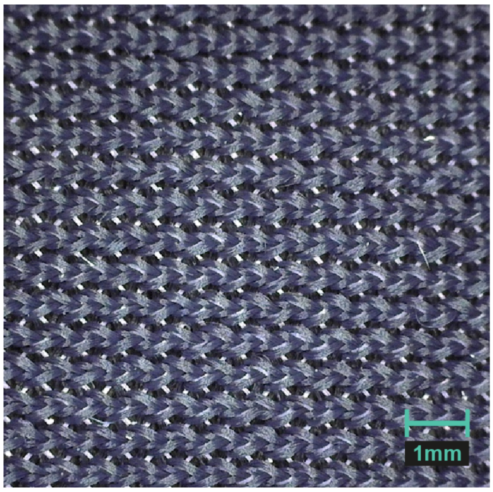
Alpha if item deleted: Only one value (0.845, highlighted in grey) is higher than the Cronbach’s alpha value achieved for the existing attitude scale. Because of the minimal difference in the values, there is no need to make changes.

Appendix EE. Case summaries of attitude scores and belief in performance- and recovery-enhancing properties of sports compression garments

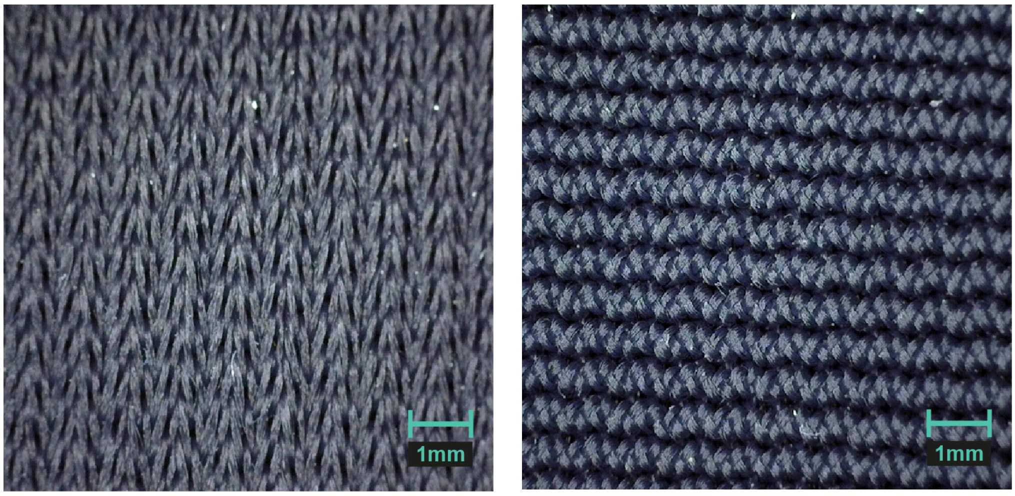
Appendix Table EE-1: Case summaries of attitude scores and belief in performance- and recovery-enhancing properties of sports compression garments

Total Attitude Score					
Do you believe that compression garments improve athletic performance?	**Do you believe that compression garments improve post-exercise recovery?**	**N**	**Median**	**Mean**	**Std. Deviation**
Yes	Yes	65	43.00	43.95	5.042
	No	6	39.00	38.33	4.761
	Total	71	43.00	43.48	5.229
No	Yes	48	37.00	37.06	4.112
	No	26	32.50	32.31	5.424
	Total	74	36.00	35.39	5.117
Total	Yes	113	41.00	41.03	5.773
	No	32	33.50	33.44	5.753
	Total	145	39.00	39.35	6.559

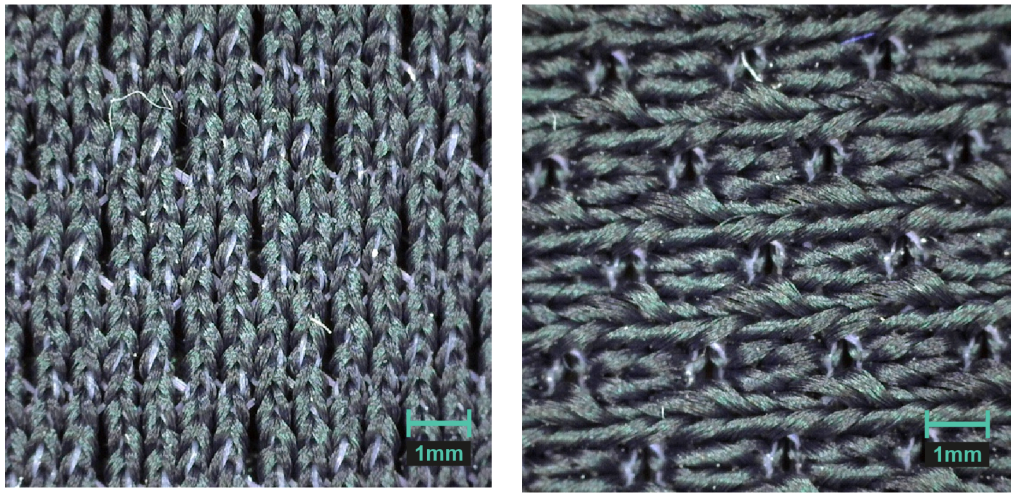
Appendix FF. Results of fabric analysis

	Technical Face	Technical Back
a)		
b)		
c)		

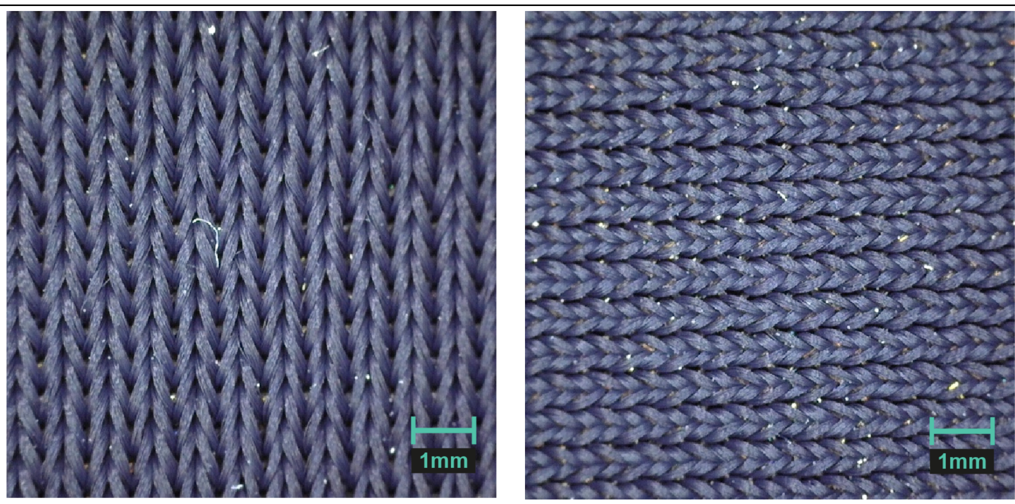
d)



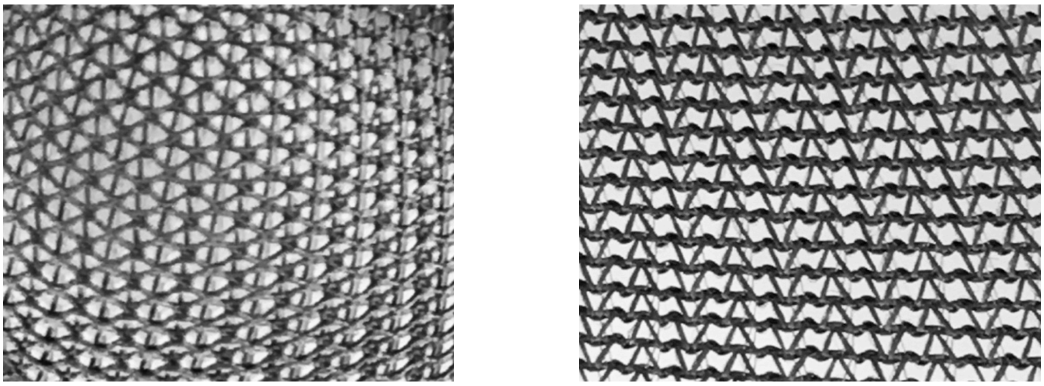
e)



f)

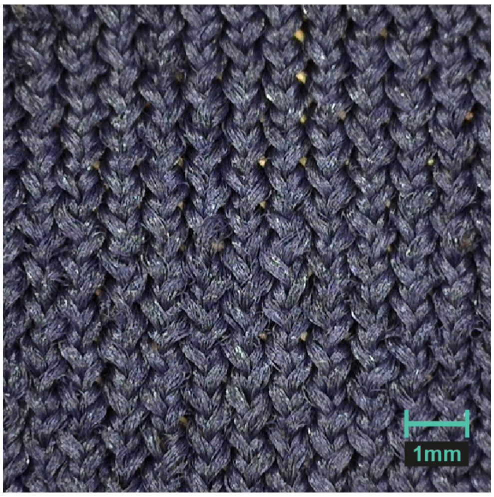
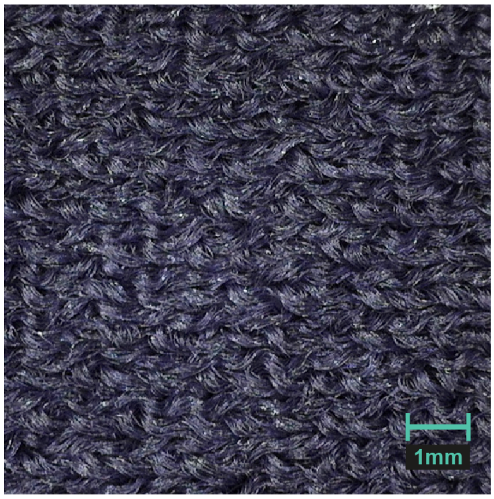
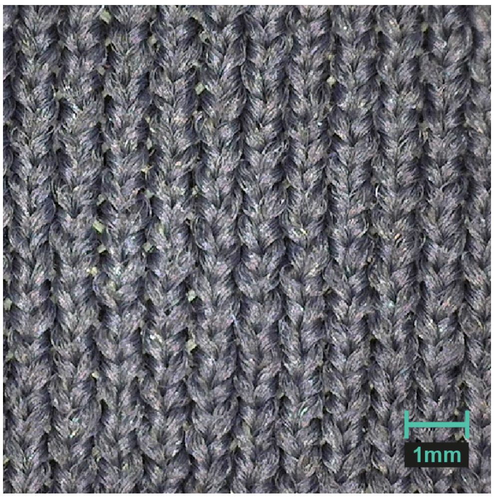
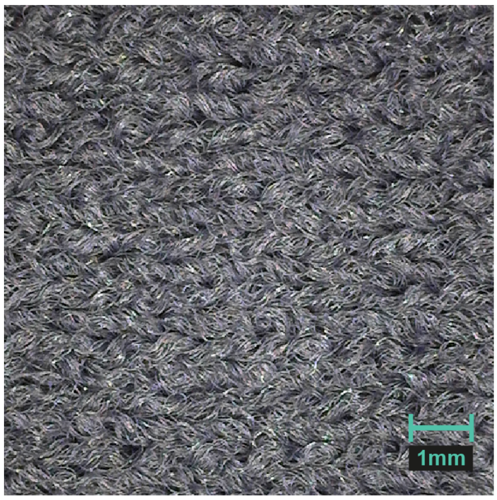


Appendix Figure FF-1: Fabrics used in Skins A400 compression garments viewed under microscope: a) Fabric A: Tricot warp knit; b) Fabric B: Sharkskin; c) Fabric C: Tricot warp knit; d) Fabric D: Tricot warp knit with weft insertion; e) Fabric E: Warp knit mesh; f) Fabric F: Tricot warp knit.



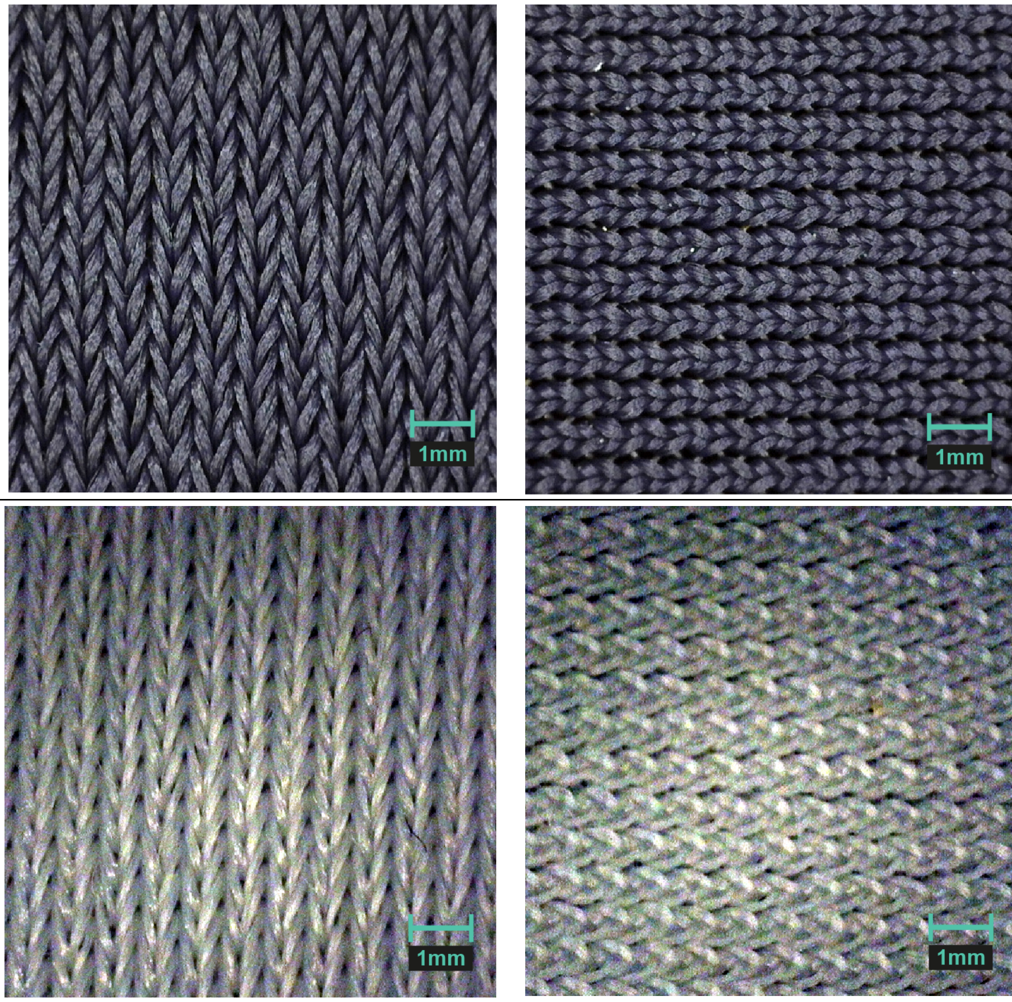
a) b)

Appendix Figure FF-2: Enlarged view of fabric structure in stretched condition: a) Fabric B featuring a sharkskin structure; b) Fabric D featuring a 1x1 tricot warp stitch with weft-inserted yarn

	Technical Face	Technical Back
a)		
b)		

c)

d)



Appendix Figure FF-3: Fabrics provided by compression garment start-up brand viewed under microscope: a) Fabric P1: Tricot warp knit - brushed; b) Fabric P2: Tricot warp knit – brushed; c) Fabric P3: Tricot warp knit; d) Fabric P4: Tricot warp knit.

Appendix Table FF-1: Properties of tested fabrics

	Fabric A	Fabric B	Fabric C	Fabric D	Fabric E	Fabric P1	Fabric P2	Fabric P3	Fabric P4
Area density (g/m^2)	206.4 (4.56)	320.8 (3.35)	111* (3.83)	240 (2.83)	212**	210.6 (4.34)	153.4 (3.65)	220 (2.83)	204.4 (4.77)
Thickness (mm)	0.66 (0.01)	0.67 (0.01)	0.41 (0.01)	0.49 (0)	0.59 (0.01)	0.61 (0.01)	0.59 (0.02)	0.61 (0.01)	0.56 (0.01)
Bulk density (g/cm^3)	0.31	0.48	0.27	0.49	0.36	0.35	0.26	0.36	0.37
Courses per cm	24.6 (0.5)	19 (0)	21 (± 0)	19 (0)	-	24.8 (0.84)	22.4 (0.55)	26 (0)	25 (0)
Wales per cm	23 (0)	14 (0)	17.4 (0.55)	15.2 (0.45)	-	22.6 (0.55)	21.2 (0.45)	23 (0)	23 (0)
Stitch density (cm^2)	565.8	266	365.4	288.8	-	560.48	474.88	598	575

**only 4 samples analysed, **only 1 sample analysed, ***only 2 samples analysed, standard deviation in parentheses*

Appendix Table FF-2: Results of stretch and recovery tests

		Fabric A	Fabric B*	Fabric C**	Fabric D***	Fabric E	Fabric F*	Fabric P1	Fabric P2	Fabric P3	Fabric P4
Extension (%)	Crosswise	195.79	105.76	-	228.29	-	-	232.63	175.26	226.32	214.74
	Lengthwise	106.45	-	227.63	73.03	-	112.17	158.95	108.95	136.58	137.11
Residual extension after 1 min (%)	Crosswise	15.92	1.32	-	8.55	-	-	17.63	17.37	11.84	11.58
	Lengthwise	3.68	-	8.55	1.32	-	4.61	7.37	10.00	6.32	5.00
Residual extension after 30 min (%)	Crosswise	13.55	0	-	4.93	-	-	15.00	11.32	8.42	8.95
	Lengthwise	1.84	-	5.26	0	-	0.99	4.21	6.32	3.95	2.37

**only four samples were tested; **only one sample was tested; ***only two samples were tested*

Appendix Table FF-3: Results of bursting strength tests

	Fabric A	Fabric P1	Fabric P2	Fabric P3	Fabric P4
Mean bursting pressure (kPa)	66.63 (±8.72)	48.87 (±0.58)	58.93 (±0.58)	52.17 (±0.25)	63.03 (±8.98)
Mean distension (mm)	70.1 (±0.1)	70.1 (±0)	70.17 (±0.12)	70.13 (±0.06)	70.13 (±0.06)
Mean time (s)	3.7 (±0.44)	2.7 (±0)	3.23 (±0.06)	2.9 (±0)	3.47 (±0.46)
Observations of bursting behaviour	All 3 samples did not burst	All 3 samples did not burst	All 3 samples did not burst	All 3 samples did not burst	All 3 samples did not burst
Bursting strength (kPa)	66.63	48.87	58.93	52.17	63.03

Standard deviation in parentheses

Appendix Table FF-4: Key results of MMT

	One-way transport from skin to outside (1-5)	Overall moisture management properties (1-5)
Fabric A	5	4.5
Fabric D	5	4.5
Fabric P1	5	3.5-4
Fabric P2	5	3.5-4
Fabric P3	5	4-4.5
Fabric P4	5	4-4.5

1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent

Appendix Table FF-5: Results of FAST

FAST 1 - Compression		Fabric A	Fabric B	Fabric C	Fabric D	Fabric E	Fabric F	Fabric P1	Fabric P2	Fabric P3	Fabric P4
Thickness at $2g/cm^2$ (mm)		0.70 (0.01)	0.72 (0)	0.51 (0.01)	0.57 (0.01)	0.76 (0.01)	0.66 (0.01)	0.74 (0)	0.72 (0.01)	0.68 (0.01)	0.66 (0.02)
Thickness at $100g/cm^2$ (mm)		0.64 (0.01)	0.64 (0)	0.38 (0.01)	0.47 (0)	0.57 (0.01)	0.55 (0.01)	0.60 (0.01)	0.58 (0.01)	0.59 (0.01)	0.56 (0.01)
Surface thickness (mm)		0.07	0.08	0.12	0.10	0.20	0.12	0.14	0.14	0.08	0.11
FAST 2 – Bending Rigidity		**Fabric A**	**Fabric B**	**Fabric C**	**Fabric D**	**Fabric E**	**Fabric F**	**Fabric P1**	**Fabric P2**	**Fabric P3**	**Fabric P4**
Bending length (mm)	Crosswise	11.17 (0.58)	14* (0.71)	13.5**	9.5**	-	-	8.17 (1.53)	21.5 (2.29)	20 (1.32)	9.17 (5.11)
	Lengthwise	11.17 (0.58)	-	-	13.5**	-	9.75 (1.77)	4.83 (1.44)	16.67 (4.25)	13.83 (4.31)	12.5 (3.12)
Bending rigidity (μN•m)	Crosswise	2.82	8.63	2.68	2.02	-	-	1.12	14.95	17.26	1.54
	Lengthwise	2.82	-	-	5.79	-	1.71	0.23	6.96	5.71	3.92

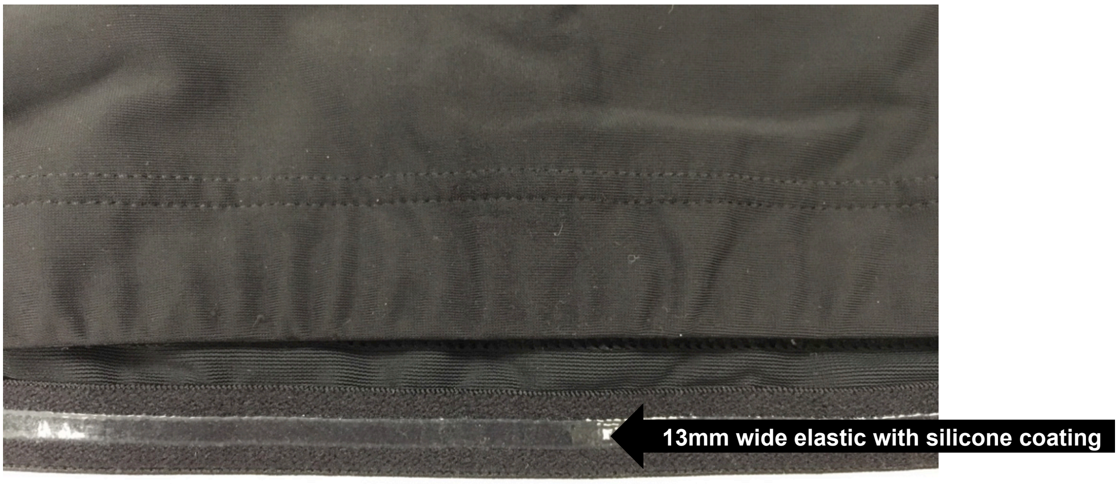
**only 2 samples tested; **only 1 sample tested; standard deviation in parentheses*

Appendix GG. Results of garment analysis

a) b) c) d) e) f)

Appendix Figure GG-1: Skins A400 Women’s Active long sleeve top and long tights on AlvaForm mannequin size 12

Appendix Figure GG-2: Waistband of compression tights with elastic at front



Appendix Figure GG-3: Hem of compression top with elastic featuring silicone coating

Appendix Table GG-1: Bill of Materials for compression top

Bill of Materials					
No.	**Item**	**Description**	**Size**	**Quantity**	**Mirrored?**
1	Fabric A	Front bodice panel	N/A	1	
2	Fabric D	Back centre panel	N/A	1	
3	Fabric A	Shoulder blade panel	N/A	2	Y
4	Fabric F	Side panel	N/A	2	Y
5	Fabric E	Underarm panel	N/A	2	Y
6	Fabric A	Sleeve panel	N/A	2	Y
7	Fabric A	Sleeve insert panel	N/A	2	Y
8	Elastic with silicone tape		13mm	71cm	
9	Care label big		N/A	1	
10	Care label small		N/A	1	

Bill of Materials					
No.	**Item**	**Description**	**Size**	**Quantity**	**Mirrored?**
11	Thread A		N/A	A/R	
12	Thread B		N/A	A/R	

Appendix Table GG-2: Bill of Materials for compression tights

Bill of Materials					
No.	**Item**	**Description**	**Size**	**Quantity**	**Mirrored?**
1	Fabric A	Front waistband panel	N/A	1	
2	Fabric B	Back waistband panel inner	N/A	1	
3	Fabric B	Back waistband panel outer	N/A	1	
4	Fabric C	Waistband pocket panel	N/A	2	Y
5	Fabric A	Front thigh panel	N/A	2	Y
6	Fabric D	Side thigh panel outer	N/A	2	Y
7	Fabric C	Side thigh panel inner	N/A	2	Y
8	Fabric A - R*	Front knee panel	N/A	2	Y
9	Fabric A	Shin panel	N/A	2	Y
10	Fabric A	Back leg panel	N/A	2	Y
11	Fabric A	Inner calf panel	N/A	2	Y
12	Fabric A	Lower calf panel	N/A	2	
13	Fabric A	Crotch panel outer	N/A	1	
14	Fabric E	Crotch panel inner	N/A	1	
15	Elastic		39mm	22cm	
16	Care label big		N/A	1	
17	Care label small		N/A	1	
18	Thread A		N/A	A/R	
19	Thread B		N/A	A/R	

Appendix Table GG-3: Garment flat measurements of the compression top

	Top - Point of Measure	Measurements (cm)		
		Size S	**Size M**	**Size L**
1	Front length (side neck point to hem)	55.4	56.3	57.1
2	Centre back length	52.9	54.2	55.4
3	Side length	38.6	39.2	38.8
4	Chest width (2.5cm down from underarm)	32.7	34.5	37.6
5	Across chest (6.5cm down from centre neck seam)	29.5	31.3	32.7
6	Across back (10cm down from centre neck seam)	28.0	28.5	29.9
7	Waist width (40cm down from shoulder high point)	28.8	30.4	33.2
8	Bottom opening width (edge to edge, straight)	32.7	34.5	37.1
9	Sleeve length top armhole (shoulder high point to sleeve opening)	58.9	59.8	61.5
10	Sleeve length underarm	45.7	46.2	47.1
11	Curved armhole width (front)	17.0	18.7	20.4

	Top - Point of Measure	Measurements (cm)		
		Size S	Size M	Size L
12	Sleeve width (2.5cm below armhole, parallel to sleeve opening)	12.9	14.0	15.0
13	Elbow width (1/2 of underarm sleeve length)	9.1	10.1	10.8
14	Sleeve opening width	6.5	7.0	7.4
15	Neck depth front	7.8	8.0	7.9
16	Neck drop front	9.1	9.1	9.3
17	Neck drop back	1.1	1.0	1.3
18	Neck width	17.5	18.2	18.9
19	Neck base	23.6	24.3	24.9

Appendix Table GG-4: Garment flat measurements of the compression tights

	Tights - Point of Measure	Measurements (cm)		
		Size S	Size M	Size L
1	Waistband depth CF	3.5	3.5	3.6
2	Waistband depth CB	6.6	6.7	6.8
3	Waistband depth side	6.6	6.7	6.7
4	Waistband width front (measured straight at top edge)	32.2	35.5	38.6
5	Hip width (10cm down from top edge)	31.8	35.6	38.7
6	Inseam (measured along seam, CF seam to hem)	69.6	69.9	70.2
7	Outseam/length (top edge to hem)	85.1	87.4	89.4
8	Front rise (top edge to crotch seam intersection, measured along curve)	18.3	20.2	22.1
9	Back rise (top edge to front seam, measured along curve)	27.6	28.2	30.3
10	Thigh width (5cm down from crotch)	17.2	18.7	20.2
11	Knee width (½ of inseam length)	11.7	12.4	13.1
12	Calf width (25cm up from bottom hem)	10.7	11.6	12.4
13	Leg opening width (measured straight)	8.6	8.9	9.1

Appendix HH. Anthropometric data of wearer trial participants

Appendix Table HH-1: Mean body dimensions of all wearer trial participants

All Wearer Trial Participants	*N* = 33	
	Mean	*SD*
Height (cm)	165.47	6.54
Weight (kg)	64.50	7.03
BMI	23.58	2.84
Chest circumference	93.42	7.01
Under bust circumference	80.23	4.89
Waist circumference	89.51	6.54
Hip circumference	103.29	5.29
Seat circumference	101.06	5.04
Inseam right	75.87	3.85
Biceps circumference right	28.78	2.08
Forearm circumference right	24.95	1.19
Wrist circumference right	16.10	1.12
Arm length right	55.05	2.67
Mid-thigh circumference right	48.17	3.36
Knee circumference right	37.42	2.29
Calf circumference right	37.63	2.53
Ankle circumference right	23.46	1.97

All length measurements in cm

Appendix Table HH-2: Results of Mann-Whitney test: Differences in body measurements across participants classed as size XS (*n* = 3) and S (*n* = 3) in compression tights

Body Measurement – Tights XS-S	*U*	*p*	Effect size *r*
Height	20	0.416	-0.17
Weight	1	0.008*	-0.56
BMI	6	0.031*	-0.46
Chest circumference	6	0.031*	-0.45
Under bust circumference	4	0.019*	-0.50
Waist circumference	2	0.011*	-0.54
Hip circumference	6	0.031*	-0.46
Seat circumference	2	0.011*	-0.54
Inseam	25	0.738	-0.07
Biceps circumference	10	0.077	-0.38
Forearm circumference	16	0.232	-0.25
Wrist circumference	9	0.062	-0.40
Arm length	21	0.473	-0.15
Mid-thigh circumference	0	0.006*	-0.58
Knee circumference	14	0.165	-0.30

Body Measurement – Tights XS-S	*U*	*p*	Effect size *r*
Calf circumference	3	0.015*	-0.52
Ankle circumference	9	0.62	-0.40

**significant difference (p < 0.05) between sizes XS and S.*
Note: r = 0.10 – 0.29 - small effect, r = 0.30 – 0.49 - medium effect, r = 0.50 – 1.0 - large effect.

Appendix Table HH-3: Results of Mann-Whitney test: Differences in body measurements across participants classed as size L (*n* = 9) and XL (*n* = 2) in compression top

Body Measurement – Tights XS-S	*U*	p	Effect size r
Height	0.00	1.000	0.00
Weight	-0.94	0.346	-0.28
BMI	-0.71	0.480	-0.21
Chest circumference	-2.12	0.034*	-0.64
Under bust circumference	-1.65	0.099	-0.50
Waist circumference	-0.24	0.814	-0.07
Hip circumference	-0.24	0.814	-0.07
Seat circumference	-0.47	0.637	-0.14
Inseam	-0.71	0.480	-0.21
Biceps circumference	-1.18	0.239	-0.36
Forearm circumference	-0.94	0.346	-0.28
Wrist circumference	-0.24	0.813	-0.07
Arm length	0.00	1.000	0.00
Mid-thigh circumference	-0.24	0.814	-0.07
Knee circumference	-0.94	0.346	-0.28
Calf circumference	-1.18	0.239	-0.36
Ankle circumference	-0.24	0.814	-0.07

**significant difference (p < 0.05) between sizes L and XL.*
Note: r = 0.10 – 0.29 - small effect, r = 0.30 – 0.49 - medium effect, r = 0.50 – 1.0 - large effect.

Appendix Table HH-4: Mean key characteristics of wearer trial participants included in analysis for compression top and tights

Wearer Trial Participants	Top (*n* = 31)		Tights (*n* = 30)	
	Mean	*SD*	Mean	*SD*
Age	30.77	8.22	30.97	8.91
Training hours per week	7.08	3.88	6.55	3.41
Height	165.48	6.42	165.12	5.96
Weight (kg)	63.79	6.50	65.40	6.67
BMI	23.33	2.72	23.99	2.60
Chest circumference	92.27	5.46	94.17	6.90
Under bust circumference	79.62	4.36	80.85	4.64
Waist circumference	89.08	6.51	90.43	6.04

Wearer Trial Participants	Top (n = 31)		Tights (n = 30)	
	Mean	*SD*	Mean	*SD*
Hip circumference	102.94	5.14	104.03	4.95
Seat circumference	100.73	4.97	101.87	4.51
Inseam right	75.98	3.88	75.89	3.89
Biceps circumference right	28.55	1.92	28.99	2.05
Forearm circumference right	24.86	1.16	25.06	1.20
Wrist circumference right	16.06	1.13	16.22	1.07
Arm length right	54.98	2.58	55.22	2.71
Mid-thigh circumference right	48.02	3.37	48.68	3.10
Knee circumference right	37.25	2.26	37.62	2.29
Calf circumference right	37.44	2.50	38.03	2.29
Ankle circumference right	23.38	1.93	23.71	1.82

All length measurements in cm

Appendix Table HH-5: Mean key characteristics of wearer trial participants for each size category of the compression tights

Tights	Small (n = 19)		Medium (n = 9)		Large (n = 2)	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Height	165.53	5.74	163.99	7.14	166.30	3.39
Weight (kg)	61.59	2.57	70.12	5.36	80.35	4.45
BMI	22.48	1.55	26.07	1.59	29.00	0.42
Chest circumference	90.52	3.73	100.32	7.41	101.18	0.90
Under bust circumference	78.98	3.29	83.44	5.23	86.93	3.42
Waist circumference	87.42	3.19	93.72	5.26	104.25	1.41
Hip circumference	101.77	4.16	106.97	3.30	112.17	2.32
Seat circumference	99.83	3.98	104.44	2.35	109.61	1.97
Inseam	76.69	3.89	74.52	4.07	74.53	0.52
Biceps circumference	27.89	1.19	30.49	1.77	32.65	1.11
Forearm circumference	24.57	1.14	25.75	0.73	26.60	0.73
Wrist circumference	16.07	1.02	16.64	1.12	15.76	1.36
Arm length right	54.91	2.67	55.60	3.03	56.42	2.30
Mid-thigh circumference	47.43	2.05	49.88	2.84	55.13	3.44
Knee circumference	36.52	1.50	38.70	1.22	43.20	2.08
Calf circumference	36.86	1.77	39.93	1.69	40.68	0.91
Ankle circumference	23.49	1.99	24.20	1.64	23.58	0.30

All length measurements in cm

Appendix Table HH-6: Mean key characteristics of wearer trial participants for each size category of the compression top

Top	Small (n = 4)		Medium (n = 18)		Large (n = 9)	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Height	160.28	3.56	166.80	7.03	165.14	5.23
Weight (kg)	57.03	3.55	61.74	2.87	70.92	6.84

Top	Small (*n* = 4)		Medium (*n* = 18)		Large (*n* = 9)	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
BMI	22.15	0.76	22.26	2.20	25.99	2.46
Chest circumference	85.38	1.58	90.42	2.93	99.02	3.16
Under bust circumference	74.50	2.34	78.52	2.59	84.10	4.09
Waist circumference	83.28	1.18	87.00	4.12	95.82	6.67
Hip circumference	101.30	5.18	101.44	4.05	106.68	5.65
Seat circumference	98.47	5.49	99.47	4.05	104.26	5.13
Inseam	73.08	2.22	76.75	4.29	75.73	3.17
Biceps circumference	27.40	0.95	27.91	1.46	30.35	1.91
Forearm circumference	25.02	0.97	24.43	1.17	25.65	0.80
Wrist circumference	15.89	1.19	15.86	1.15	16.55	1.05
Arm length	53.85	1.96	55.05	2.60	55.33	2.88
Mid-thigh circumference	46.88	3.16	47.15	2.40	50.28	4.32
Knee circumference	36.09	1.81	36.77	1.61	38.72	2.95
Calf circumference	36.94	2.08	36.63	2.37	39.30	2.08
Ankle circumference	23.74	1.47	22.96	2.26	24.06	1.14

All length measurements in cm

Appendix Table HH-7: Results of t-tests: Differences in body measurements between sizes S and M of the compression tights

Tights (*n* = 30)	*df*	*t*	*p*
Height	26	0.615	0.544
Weight	26	-4.529	0.001*
BMI	26	-5.658	<0.001*
Waist circumference	26	-3.951	0.001*
Hip circumference	26	-3.282	0.003*
Seat circumference	26	-3.196	0.004*
Inseam right	26	1.353	0.188
Mid-thigh circumference	26	-2.605	0.015**
Knee circumference	26	-3.800	0.001*
Calf circumference	26	-4.343	<0.001*
Ankle circumference	26	-0.933	0.360

**significant difference (p < 0.01) in body measurements between sizes*
***significant difference (p < 0.05) in body measurements between sizes*

Appendix Table HH-8: Results of Kruskal-Wallis test with post-hoc Mann-Whitney tests: Differences in body measurements across the three sizes of the compression top

Top (*n* = 31)	*df*	*H*	*p*	Mann-Whitney post-hoc *p*		
				S-M	S-L	M-L
Height	2	3.906	0.142	-	-	-
Weight	2	17.572	<0.001	0.027	0.005*	<0.001*
BMI	2	10.862	0.004	0.898	0.014*	0.002*
Chest circumference	2	22.185	<0.001	0.004*	0.005*	<0.001*
Under bust circumference	2	14.386	0.001	0.041	0.005*	0.002*

Top (*n* = 31)	***df***	***H***	***p***	**Mann-Whitney post-hoc *p***		
				S-M	S-L	M-L
Waist circumference	2	14.338	0.001	0.027	0.009*	0.002*
Hip circumference	2	6.833	0.033	0.932	0.123	0.010*
Biceps circumference	2	10.780	0.005	0.419	0.014*	0.003*
Forearm circumference	2	6.561	0.038	0.307	0.280	0.014*
Wrist circumference	2	1.706	0.426	-	-	-
Arm length right	2	0.663	0.718	-	-	-

**significant difference (p < 0.05) in body measurements between sizes*

Appendix Table HH-9: Body volumes of the wearer trial participants for each size category for the compression tights and top

	Volume (cm^3)	**Small**		**Medium**		**Large**	
		Mean	***SD***	**Mean**	***SD***	**Mean**	***SD***
Tights	Whole body volume	63502.5	2507.9	72137.3	5199.9	81267.1	3124.3
Tights	Right leg volume	9057.8	779.3	9892.8	1278.9	10581.2	643.5
Top	Whole body volume	59002.9	4119.8	63407.6	3311.8	72352.0	6248.1
Top	Torso volume	35956.4	1909.9	39652.1	2119.7	46276.8	4330.3
Top	Right bust volume	416.6	32.2	514.3	221.0	763.9	183.6

Appendix Table HH-10: Variations in circumference measurements within each size category of compression tights and top

Tights - size S	
Minimum hip circumference: 92.6cm	Maximum hip circumference: 107.7cm
	

Tights – size M	
Minimum hip circumference: 103.5cm	Maximum hip circumference: 113.1cm
	
Tights - size S	
Minimum mid-thigh circumference: 42.69cm	Maximum mid-thigh circumference: 49.76cm
	
Tights - size M	
Minimum mid-thigh circumference: 43.18cm	Maximum mid-thigh circumference: 50.76cm
	

Top – size S	
Minimum waist circumference: 82.4cm	Maximum waist circumference: 85cm
	
Top – size M	
Minimum waist circumference: 76.2cm	Maximum waist circumference: 92.9cm
	
Top – size L	
Minimum waist circumference: 84.9cm	Maximum waist circumference: 105.3cm
	

Appendix Table HH-11: Spearman's correlation between body measurements and garments flat measurements of compression tights

Correlation		Spearman's rho	*p*
Body Measurement	**Garment Flat Measurements - Tights**		
Waist circumference	Waistband width	0.67	<0.001*
Hip circumference	Hip width	0.66	<0.001*
Knee circumference	Knee width	0.69	<0.001*
Calf circumference	Calf width	0.74	<0.001*
Ankle circumference	Leg opening width	0.13	0.508
Height	Inseam	-0.04	0.831
Height	Outseam	-0.04	0.831

Note: 0.00 - 0.50 negligible correlation; 0.50-0.7 moderate correlation; 0.70-0.90 strong correlation; 0.90-1.0 very strong correlation.
**Significant correlation*

Appendix Table HH-12: Spearman's correlation between body measurements and garments flat measurements of compression top

Correlation		Spearman's rho	*P*
Body Measurement	**Garment Flat Measurements – Top**		
Chest circumference	Chest width	0.86	<0.001*
Waist circumference	Waist width	0.69	<0.001*
Hip circumference	Lower hem width	0.42	0.020*
Biceps circumference	Sleeve width	0.58	0.001*
Wrist circumference	Sleeve opening width	0.21	0.250
Arm length	Sleeve length	0.14	0.451
Height	Front length	0.16	0.380

Note: 0.00 - 0.50 negligible correlation; 0.50-0.7 moderate correlation; 0.70-0.90 strong correlation; 0.90-1.0 very strong correlation.
**Significant correlation*

Appendix II. Body shape classification of wearer trial participants

Appendix Table II-1: Final body shape evaluation based on results from categorisations according to Makhanya et al. (2014), Gribbin (2014) and Rasband and Liechty (2006)

Triangle:	
1FA23 M-M 	**3FF23 L-L** 
16FA26 M-L 	**17FA25 S-M** 

25FA28 S-M 	**26FR22 S-S** 
33FA24 L-L 	**A475 S-S** 
A476 S-M 	**A479 S-S** 

A480 S-M 	**A482 S-L** 
A488 S-M 	**A510 S-M** 
A525 M-L 	**A526 S-M** 

A527 S-S

A530 S-M

A531 M-M

A534 S-M

A536 S-M

31FA46 M-L

32FA34 S-M	**37FZ33 S-M**
	
Hourglass	
13FA23 M-L	**35FA30 S-M**
	
A013 S-M	**A024 M-L**
	

A484 M-L 	**A485 S-M** 
Inverted triangle:	
27FA47 M-L 	**A537 S-L** 
Rectangle:	
A194 S-M 	

Appendix JJ. Results of fit analysis

The fit assessment utilised the fit assessment score table in Appendix U. The score legends were as follows:

- Lengths:
  - 1: too short
  - 2: short
  - 3: good fit
  - 4: long
  - 5: too long
- Seam positioning; Fabric creases and folds:
  - 1: unsatisfactory
  - 2: normal
  - 3: satisfactory
- Waistband:
  - 1: too tight
  - 2: tight
  - 3: good fit
  - 4: loose
  - 5: too loose

Appendix Table JJ-1: Results of fit assessment for compression tights

Tights (*n* = 30)	Median	Mode	Range	Minimum	Maximum
Length - tights front	3	3	4	1	5
Length - tights back	3	3	4	1	5
Mean - length tights	3	3	4	1	5
Seam positioning tights - front	2.5	3	2	1	3
Seam positioning tights - back	2	2	1	2	3
Mean - seam pos. tights	2.5	2	1.5	1.5	3
Waistband - front	2	2[a]	2	1	3
Waistband - back	2	2	2	1	3
Mean - Waistband	2	2	2	1	3
Fabric folds ankles - front	2	3	2	1	3
Fabric folds ankles - back	2	2	2	1	3
Mean - folds ankles	2	1	2	1	3
Fabric folds shins - front	3	3	2	1	3
Fabric folds calves - back	3	3	1	2	3
Mean - folds shins/calves	3	3	1.5	1.5	3
Fabric folds knees - front	3	3	1	2	3
Fabric folds knees - back	3	3	2	1	3
Mean - folds knees	2.5	3	1.5	1.5	3
Fabric folds thighs - front	3	3	0	3	3

Tights (*n* = 30)	Median	Mode	Range	Minimum	Maximum
Fabric folds thighs - back	3	3	1	2	3
Mean - folds thighs	3	3	0.5	2.5	3
Fabric folds crotch - front	3	3	1	2	3
Fabric folds crotch - back	3	3	1	2	3
Mean - folds crotch	3	3	1	2	3
WT Questionnaire overall fit tights	4	5	2	3	5

Appendix Table JJ-2: Results of fit assessment for compression top

Top (*n* = 31)	Median	Mode	Range	Minimum	Maximum
Length torso - front	3	3	2	2	4
Length torso - back	3	3	2	2	4
Mean - length torso	3	3	2	2	4
Length sleeves - front	5	5	3	2	5
Length sleeves - back	5	5	3	2	5
Mean - length sleeves	5	5	3	2	5
Seam positioning top - front	3	3	2	1	3
Seam positioning top - back	3	3	2	1	3
Mean - seam pos. top	3	3	2	1	3
Fabric folds torso - front	3	3	2	1	3
Fabric folds torso - back	1	1	2	1	3
Mean - folds torso	2	2	2	1	3
Fabric folds shoulders - front	2	3	2	1	3
Fabric folds shoulders - back	3	3	1	2	3
Mean - folds shoulders	2.5	2.5	1	2	3
Fabric folds underarm - front	2	2	2	1	3
Fabric folds underarm - back	3	3	1	2	3
Mean - folds underarm	2.5	2.5	1.5	1.5	3
Fabric folds upper sleeves - front	2	2	2	1	3
Fabric folds upper sleeves - back	2	3	2	1	3
Mean - folds upper sleeves	2	3	2	1	3
Fabric folds lower sleeves - front	1	1	2	1	3
Fabric folds lower sleeves - back	1	1	2	1	3
Mean - folds lower sleeves	1	1	2	1	3
WT Questionnaire overall fit top	4	4	3	2	5

Appendix Table JJ-3: Spearman's correlation between body measurements and fit assessment results

Correlation		Spearman's rho	*p*
Body measurement	**Fit assessment criterion**		
Arm length right	Mean – length sleeve	-0.46	0.009
Arm length right	Mean – folds lower sleeves	0.25	0.180
Inseam length right	Mean – length tights	-0.54	0.002
Inseam length right	Mean – folds ankles	0.48	0.007
Waist circumference	Mean – length torso	0.20	0.270
Waist circumference	Mean - waistband	-0.45	0.012
Waist circumference	Mean – folds torso	-0.37	0.844

Appendix Table JJ-4: Results of Kruskal-Wallis tests to identify potential differences in fit ratings for different garment sizes

Fit criterion	*df*	*H*	*p*
Length of tights	2	0.547	0.761
Tightness of waistband	2	2.283	0.319
Fabric folds at ankle	2	0.993	0.609
Length of torso	2	2.104	0.349
Length of sleeves	2	3.203	0.202
Fabric folds at torso	2	2.815	0.245
Fabric folds at shoulder	2	2.679	0.262

Tights: n = 30; Top: n = 31

Appendix Table JJ-5: Results of Kruskal-Wallis tests to identify potential differences in fit ratings for different body shapes

Fit criterion	*df*	*H*	*p*
Length of tights	3	5.851	0.119
Tightness of waistband	3	3.430	0.330
Fabric folds at ankle	3	5.544	0.136
Length of torso	3	3.082	0.379
Length of sleeves	3	4.461	0.216
Fabric folds at torso	3	1.999	0.573
Fabric folds at shoulder	3	4.622	0.202

Tights: n = 30; Top: n = 31

Appendix KK. Results of pressure analysis

Appendix Table KK-1: Correlations between pressure measurements and body circumferences

	Correlation		Size	Spearman's rho	*p*
	Pressure Measurements	Body Circumference			
TIGHTS	B11	Ankle	S	0.38	0.112
			M	-0.93	0.812
	B31	Calf	S	0.31	0.201
			M	0.23	0.548
	B41	Knee	S	0.12	0.639
			M	0.58	0.101
	B51	Mid-thigh	S	0.41	0.080
			M	0.60	0.090
	B61	Hip	S	0.30	0.213
			M	0.83	0.006*
	B71	Hip	S	0.45	0.056
			M	-0.24	0.539
	B91	Waist	S	0.21	0.380
			M	0.48	0.192
TOP	T11	Hip	S	-0.21	0.789
			M	0.19	0.454
			L	-0.03	0.949
	T41	Waist	S	0.90	0.106
			M	0.26	0.300
			L	0.61	0.084
	T111	Biceps	S	0.74	0.260
			M	0.43	0.075
			L	0.89	0.001*
	T121	Forearm	S	0.40	0.600
			M	0.33	0.179
			L	0.65	0.060
	T131	Wrist	S	0.78	0.225
			M	0.36	0.143
			L	0.01	0.983

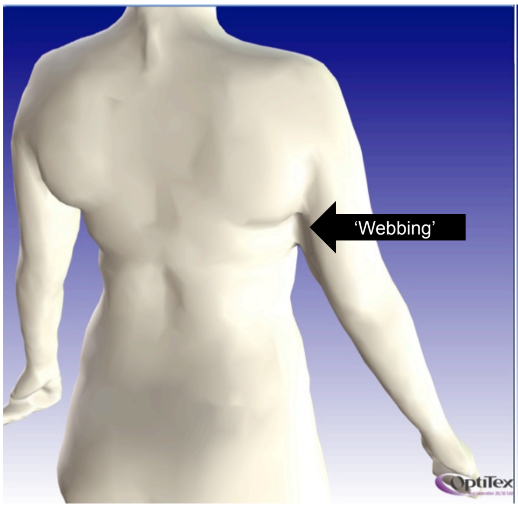
*significant correlation ($p < 0.01$)

Appendix Table KK-2: Spearman's correlation between pressure and garment stretch measurements of compression tights and top

	Correlation		Size	Spearman's rho	*p*
	Pressure Measurements	Garment Stretch Percentage			
TIGHTS	B11	Ankle	S	0.16	0.403
			M	0.38	0.112
	B31	Calf	S	0.31	0.201
			M	0.23	0.548
	B41	Knee	S	0.12	0.639
			M	0.58	0.101
	B51	Mid-thigh	S	0.41	0.080
			M	0.60	0.090
	B61	Hip	S	0.34	0.159
			M	0.82	0.007*
	B71	Hip	S	0.45	0.056
			M	-0.24	0.539
	B81	Hip	S	-0.06	0.811
			M	-0.05	0.897
	B91	Waist	S	0.21	0.380
			M	0.48	0.192
TOP	T11	Hip	S	-0.21	0.789
			M	0.19	0.454
			L	-0.03	0.949
	T21	Waist	S	-0.95	0.051
			M	0.31	0.216
			L	0.66	0.055
	T31	Waist	S	0.32	0.684
			M	-0.02	0.961
			L	0.42	0.264
	T41	Waist	S	0.89	0.106
			M	0.26	0.300
			L	0.61	0.084
	T111	Biceps	S	0.74	0.262
			M	0.43	0.075
			L	0.89	0.001*
	T121	Forearm	S	0.40	0.600
			M	0.33	0.179
			L	0.65	0.060
	T131	Wrist	S	0.78	0.225
			M	0.36	0.143
			L	0.01	0.983

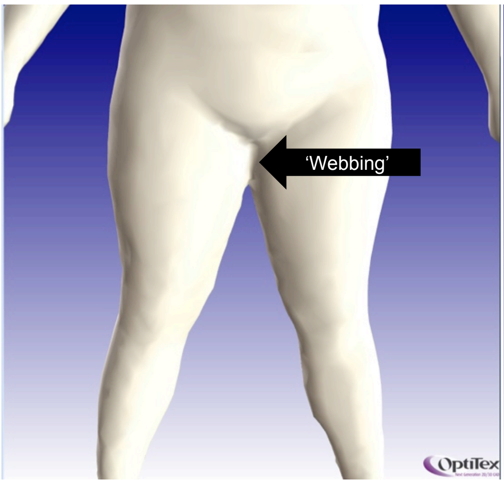
*significant difference ($p < 0.01$)

Appendix LL. Problems with using original body scan files for virtual fit



a) b)

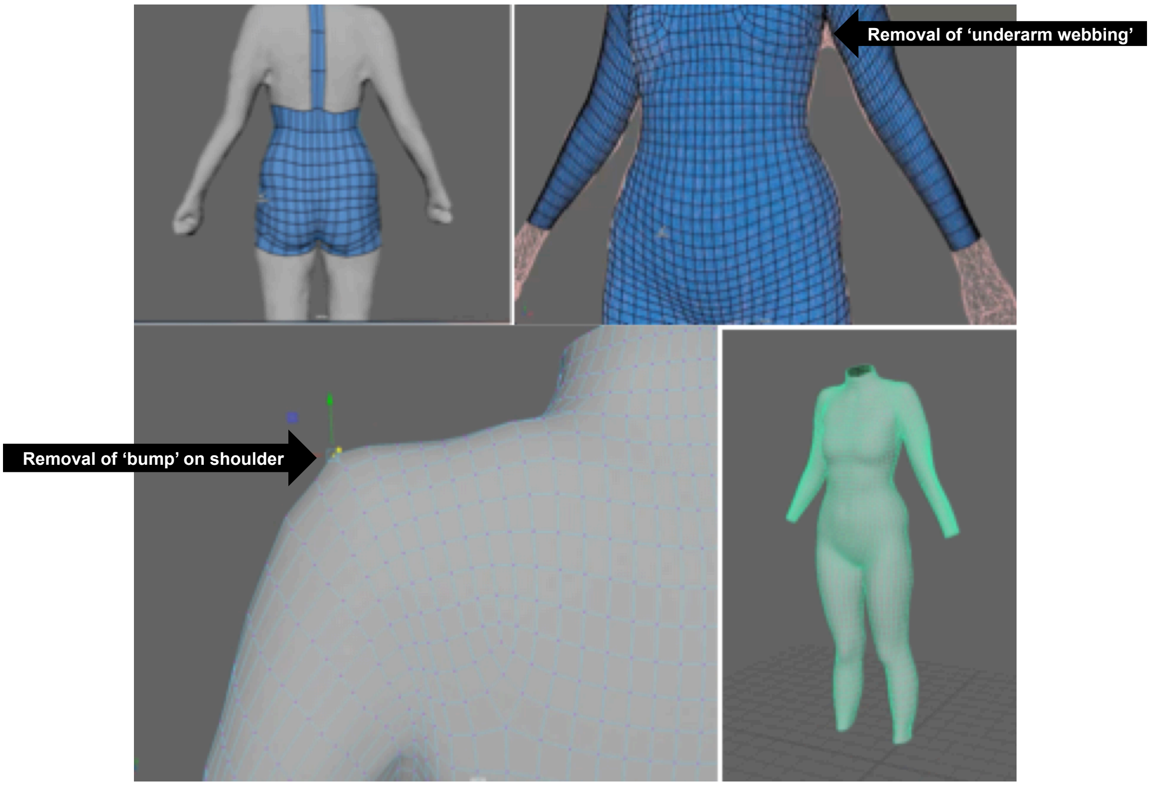
Appendix Figure LL-1: Refined Body Mesh (RBM) with 'webbing' in armpit (a) and virtual fit attempt with compression top (b)



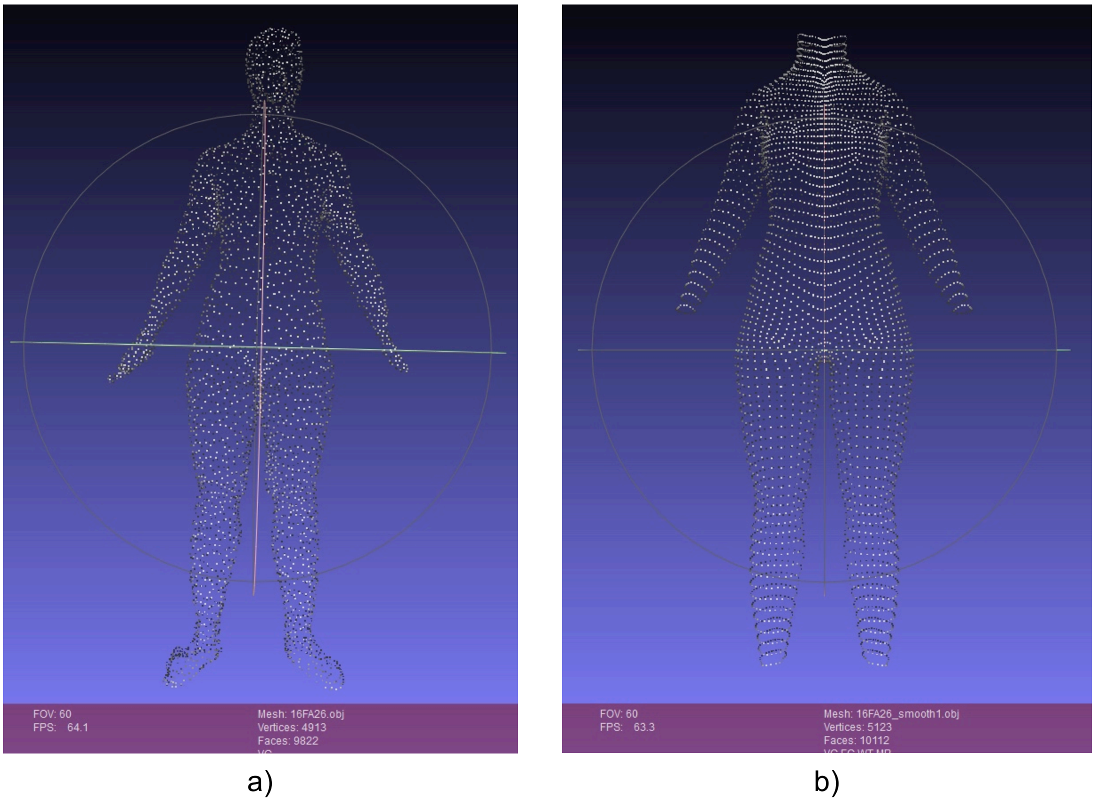
a) b)

Appendix Figure LL-2: RBM with 'webbing' in crotch area (a) and virtual fit attempt with compression tights (b)

Appendix MM. Remodelling of original body scan files



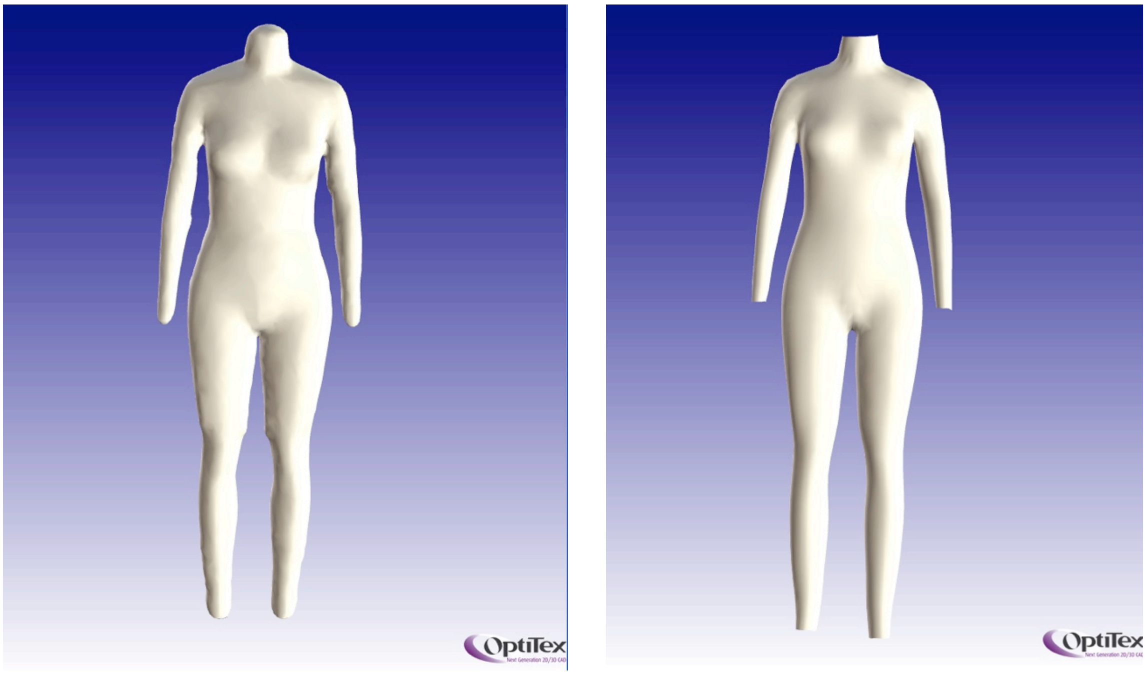
Appendix Figure MM-1: Difference stages of the remodelling process



Appendix Figure MM-2: Different stages of the remodelling process: a) point clouds of the original body scan file (RBM); b) point cloud of the remodelled body avatar with points arranged in straight lines.

Appendix Table MM-1: Percentage differences between circumference measurements of the RBMs and remodelled body avatars obtained using the Optitex circumference tool

Participant	Narrow waist	Seat	Right Thigh	Right Knee
A013	0.66%	-1.16%	-2.42%	-4.78%
A476	-0.32%	-2.56%	-2.65%	-1.03%
A024	0.37%	0.73%	-1.96%	3.53%
A194	0.04%	0.04%	-1.77%	-0.13%
A530	-0.78%	0.53%	-0.53%	-2.84%
1FA23	1.67%	-2.03%	-0.25%	0.03%
13FA23	0.00%	0.59%	-0.51%	-0.07%
17FA25	1.91%	-1.44%	-1.18%	-5.54%
25FA28	-1.23%	0.06%	-1.45%	-0.90%
26FR22	-0.71%	-0.85%	-1.02%	-2.41%
27FA47	0.03%	-0.29%	-6.17%	-3.63%
31FA46	0.30%	0.03%	-2.06%	-3.32%
32FA34	0.12%	0.55%	-1.85%	3.32%
35FA30	-0.04%	1.09%	-1.30%	-0.88%
37FZ33	0.33%	-1.48%	-0.53%	-0.28%
Mean difference:	0.16%	-0.41%	-1.71%	-1.26%



a) b)

Appendix Figure MM-3: Comparison of remodelled OBJ file of scanned mannequin and real mannequin: a) original scan of mannequin; b) remodelled avatar of mannequin with smoother surface and no 'webbing' in underarm and crotch areas

The circumference measurement tool in Optitex was used to obtain measurements of the remodelled mannequin avatar. Then differences between the measurements to manual measurements of mannequin were calculated:

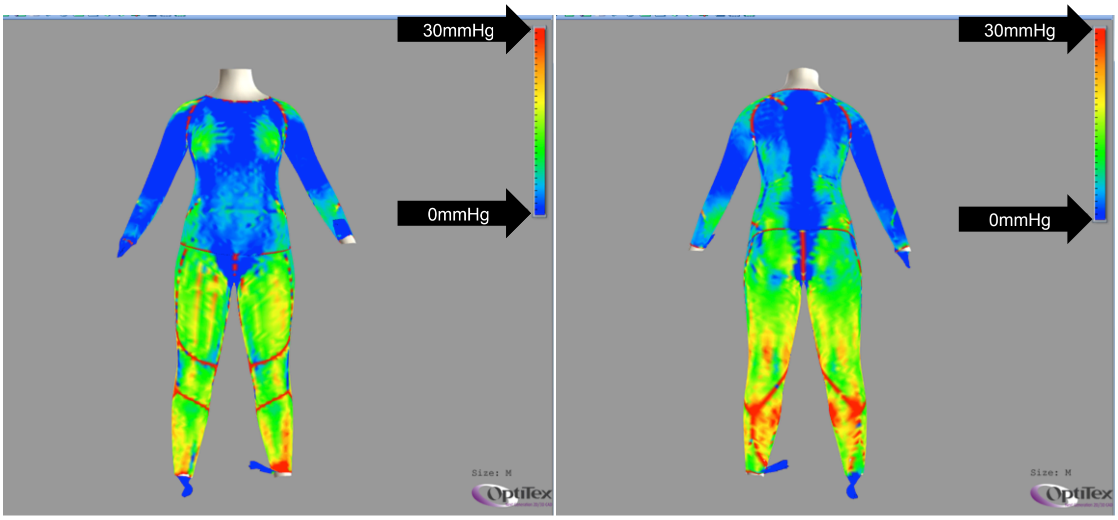
Appendix Table MM-2: Comparison of measurements of real mannequin and remodelled scan of mannequin

Measurement	Real mannequin manual (GG)	Smooth OBJ in Optitex	Absolute diff.	Percentage difference
Chest girth	90.5	87.9	-2.6	-2.87
Waist girth (min.)	70.5	70.3	-0.2	-0.28
Hip girth (max.)	97	96	-1	-1.03
Thigh girth	57	55	-2	-3.51
Knee girth	34	35.4	1.4	4.12
Calf girth	34.5	33.5	-1	-2.90
Ankle girth	22.5	21.7	-0.8	-3.56
		Mean difference:	-0.89	-1.43

All length measurements in cm

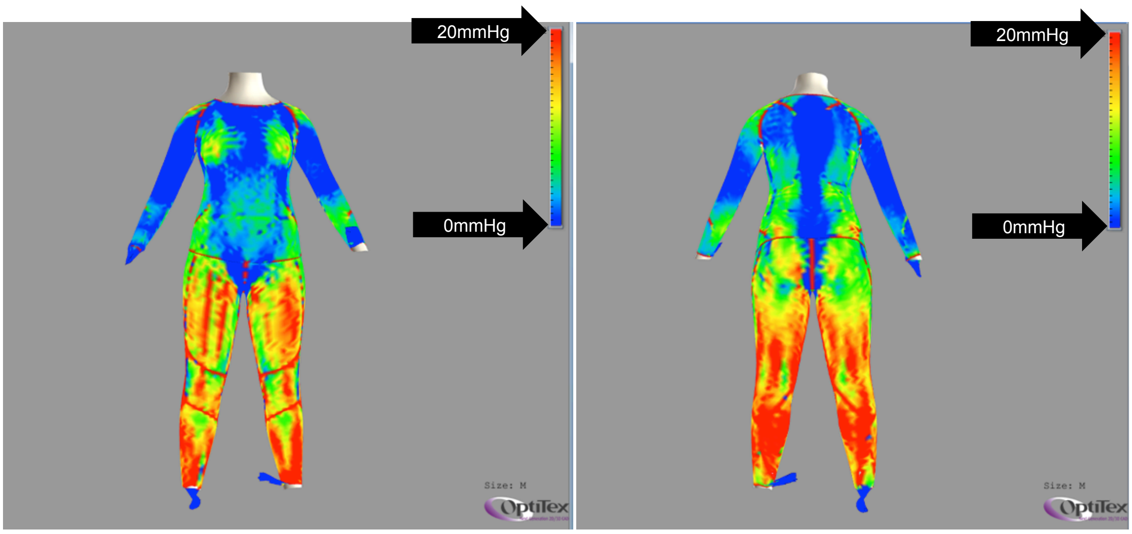
Appendix NN. NCP maps with varying maximum pressure limits

Changing the maximum displayed pressure value gives a better visual representation of the pressure distribution across the body, as the unrealistically high pressure levels of the seams are eliminated. It is evident from the Figures below that pressures at the legs were higher that pressure levels at the top with the lowest pressure levels present at the upper arms and spine.



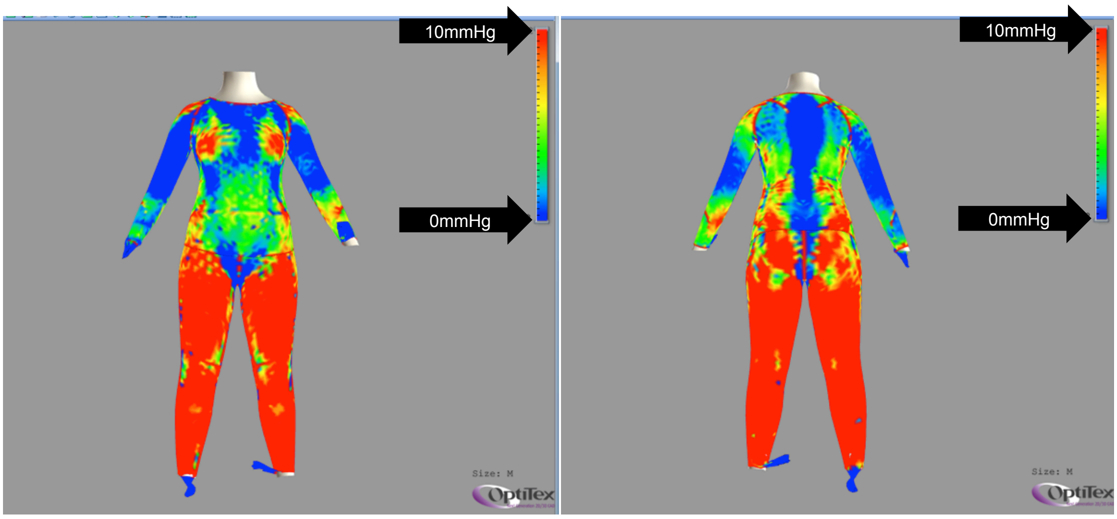
a) b)

Appendix Figure NN-1: NCP map of compression tights and top on remodelled body avatar in Optitex with max. NCP set as 30mmHg: (a) front view; (b) back view



a) b)

Appendix Figure NN-2: NCP map of compression tights and top on remodelled body avatar in Optitex with max. NCP set as 20mmHg: (a) front view; (b) back view



a) b)

Appendix Figure NN-3: NCP map of compression tights and top on remodelled body avatar in Optitex with max. NCP set as 10mmHg: (a) front view; (b) back view

Appendix OO. Garment stretch percentage of compression tights when worn by wearer trial participants

Appendix Table OO-1: Garment stretch percentage at B51, B41 and B31 for participants included in the pressure analysis

Participant	Size	Garment stretch (%)		
		B51 - Mid-thigh	B41 - Knee	B31 - Calf
1FA23	M	33.73	58.02	69.35
13FA23*	M	40.80	63.83	76.93
17FA25*	S	32.97	54.03	59.72
26FA22*	S	42.24	51.29	72.38
27FA47*	M	30.21	58.99	74.37
31FA46	M	26.62	56.81	68.35
32FA34*	S	36.94	51.20	73.69
37FZ33*	S	42.22	55.36	64.02
A013FA25	S	29.01	52.79	64.86
A024FA23*	M	27.00	48.39	63.25
A194FA40*	S	43.53	63.73	74.49
A476FA22*	S	47.23	66.09	78.36
A530FA24*	S	31.75	61.67	66.96

**Simulation with fabric gaps*

Appendix Table OO-2: Mean garment stretch percentage at B51, B41 and B31 across all wearer trial participants

Tights (*n* = 30)	Mean garment stretch (%)		
	S	M	L
B51 – Mid-thigh	38.27	33.73	36.46
B41 - Knee	56.72	56.05	64.89
B31 - Calf	72.24	72.86	64.70

Appendix PP. Reliability check of garment simulation in Optitex

Appendix Table PP-1: Results of reliability check of garment simulation in Optitex

Avatar	1st		2nd		3rd	
	Tights	Top	Tights	Top	Tights	Top
1FA23	✓	✓	✓	✓	Problem at lower leg	✓
13FA23	✓	✓	✓	✓	Difference at ankles	Failed
17FA25	Hole at calf	Difference at wrist	Big hole on calf	Slight difference on wrists	Failed	Difference at wrists
25FA28	Failed	Failed	Failed	Failed	Difference at ankles	Problems with sleeves
26FA22	✓	✓	✓	✓	Difference at ankles	Failed
27FA47	✓	✓	✓	✓	Difference at ankles	Difference at wrists
31FA46	✓	✓	✓	✓	Difference at ankles	Failed
32FA34	✓	Failed	Slight difference at ankles	Failed, but works on its own	Difference at ankles	Difference at wrists
35FA30	✓	✓	✓	✓	Difference at ankles	Failed
37FZ33	Difference at right ankle	Difference at right wrist	Big hole at lower calf	Slight difference at wrists	Big hole at lower calf	Failed
A013FA25	Difference at ankles	Difference at wrists	Difference at ankles	Difference at wrists	Difference at ankles	Big hole on lower sleeve
A024FA23	✓	✓	✓	✓	Problem at ankle	Difference at wrists
A194FA40	✓	✓	✓	✓	Problem at ankle	✓
A476FA22	✓	✓	✓	✓	Problem at ankle	Failed
A530FA24	Problem at ankle	Failed	Problem at ankle	Failed, but works on its own	Problem at ankle	Difference at wrists

Appendix QQ. Final simulation results of virtual wearer trials

Appendix Table QQ-1: Final simulations for virtual wearer trial participants

<table>
<tr><td colspan="2">1FA23 – tights: M, top: M</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">13FA23 – tights: M, top: L</td></tr>
<tr><td></td><td></td></tr>
</table>

17FA25 – tights: S, top: M	
	
25FA28 – tights: S, top: M	
	

26FA22 – tights: S, top: S


27FA47 – tights: M, top: L


31FA46 – tights: M, top: L	
	
32FA34 – tights: S, top: M	
	

<table>
<tr><td colspan="2">35FA30 – tights: S, top: M</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">37FZ33 – tights: S, top: M</td></tr>
<tr><td></td><td></td></tr>
</table>

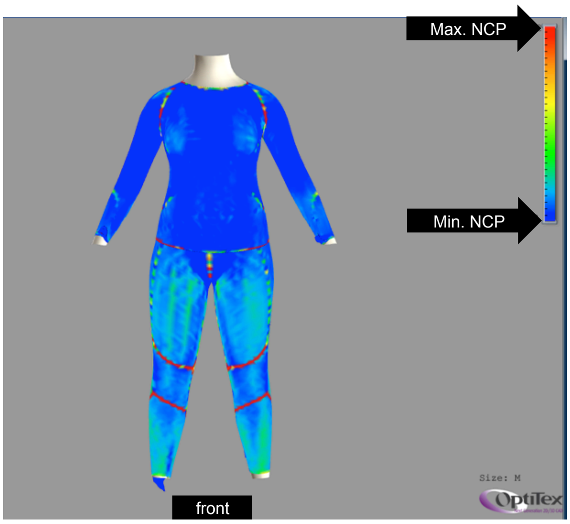
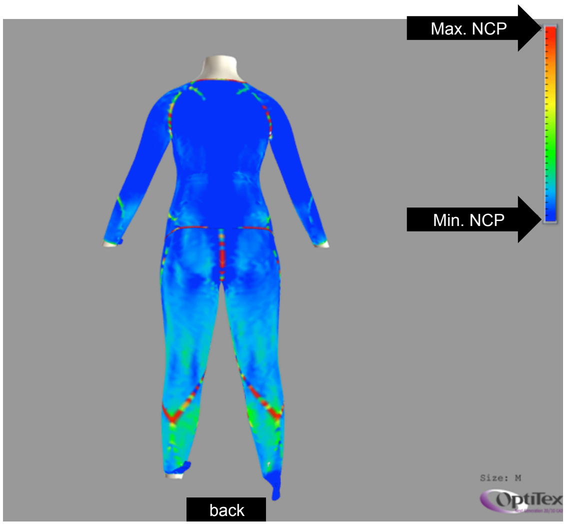
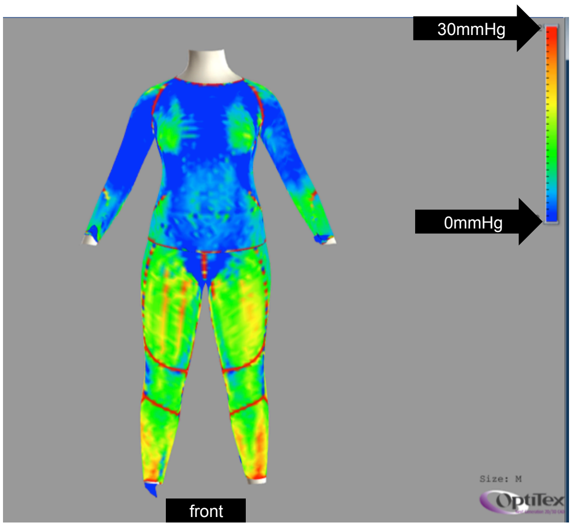
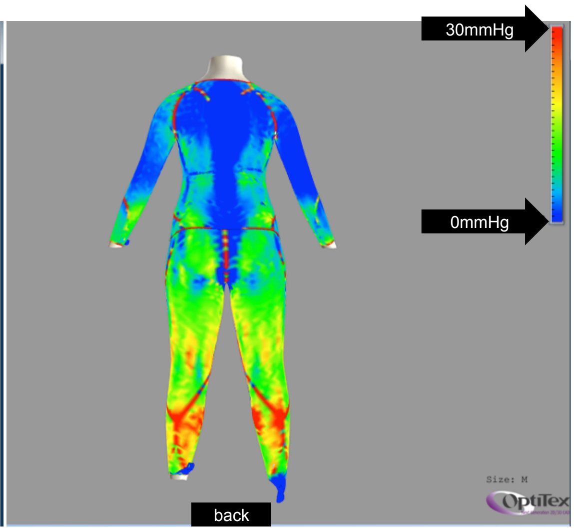
<table>
<tr><td colspan="2">A013FA25 – tights: S, top: M</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">A024FA23 – tights: M, top: L</td></tr>
<tr><td></td><td></td></tr>
</table>

A194FA40 – tights: S, top: M	
	
A476FA22 – tights: S, top: M	
	

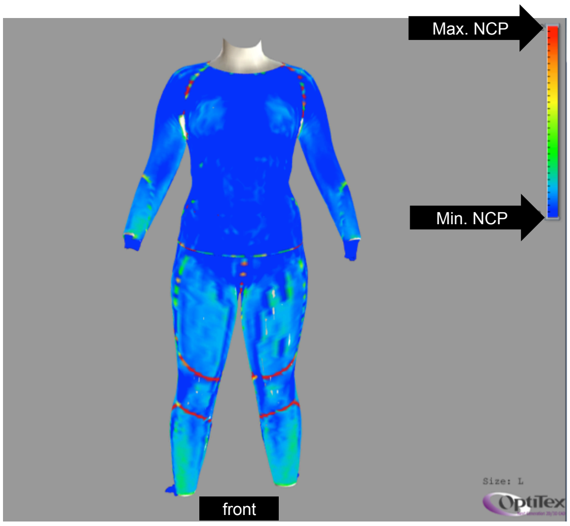
A530FA24 – tights: S, top: M	
	

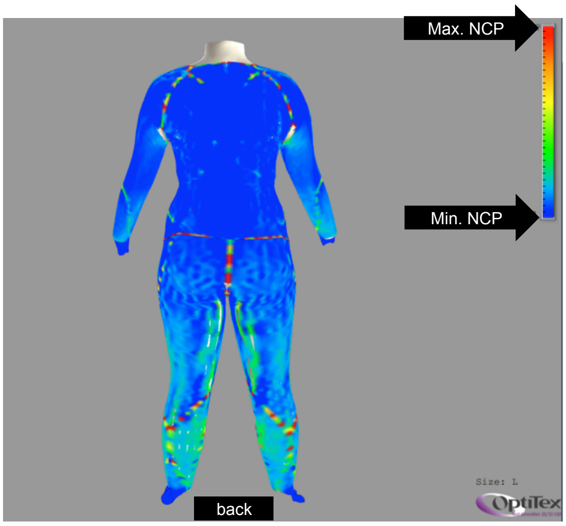
Appendix RR. Normal collision pressure maps used for virtual pressure analysis

Appendix Table RR-1: Normal collision pressure maps for virtual wearer trial participants with maximum NCP as per default settings and maximum NCP set as 30mmHg

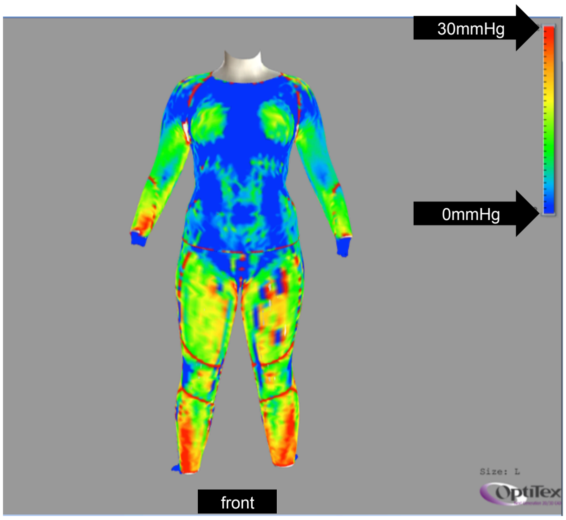
1FA23 – M-M - Normal collision pressure:	
	
1FA23 – M-M - Normal collision pressure set as max. 30mmHg:	
	

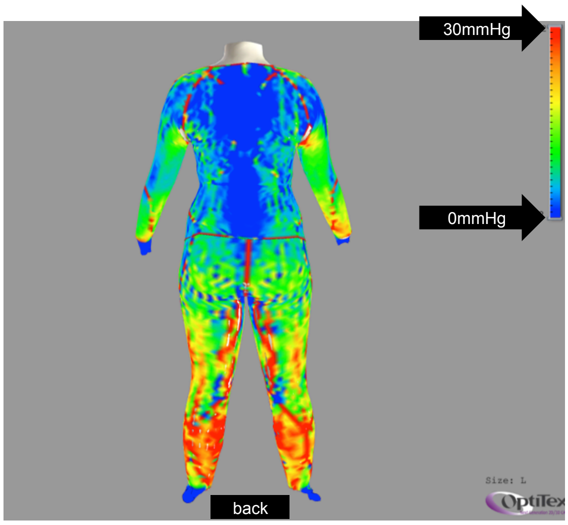
13FA23 – M-L - Normal collision map:



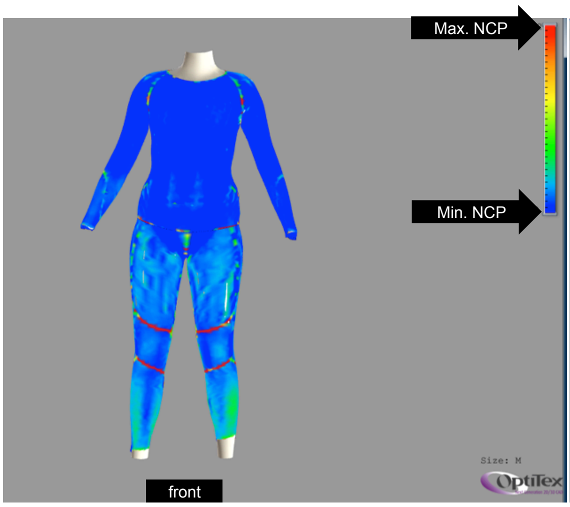


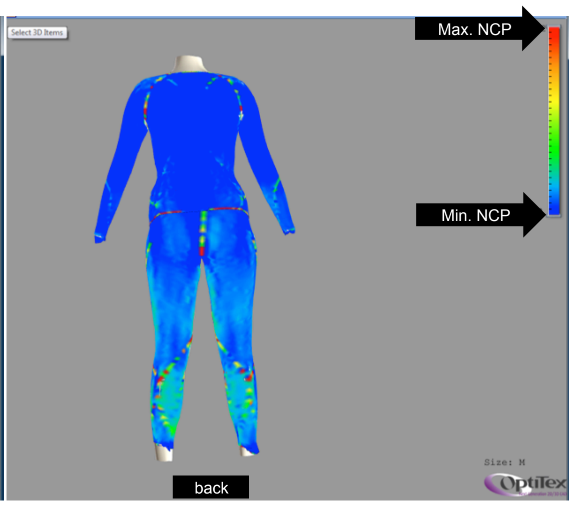
13FA23 – M-L - Normal collision pressure set as max. 30mmHg:



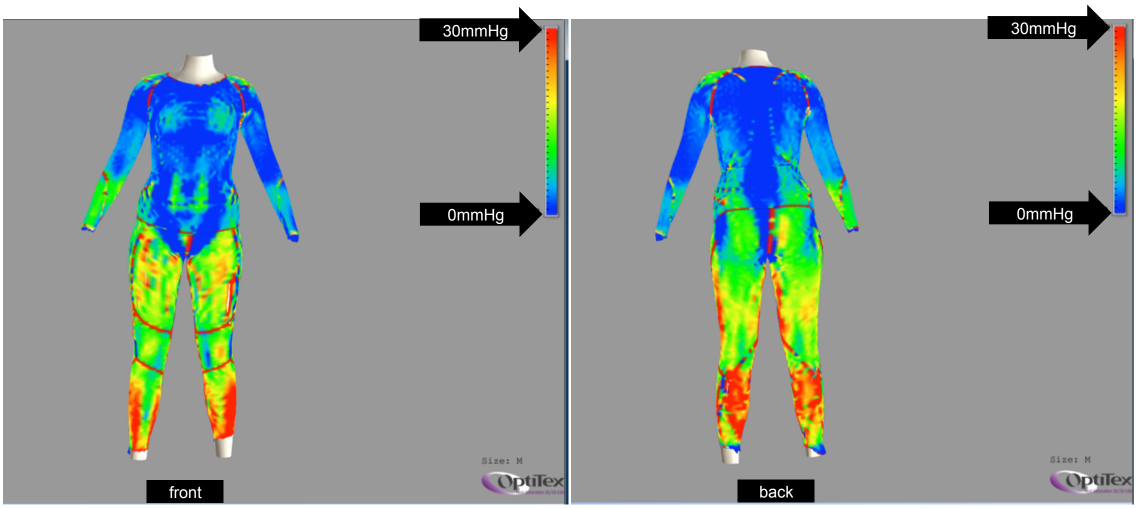


17FA25 – S-M - Normal collision map:

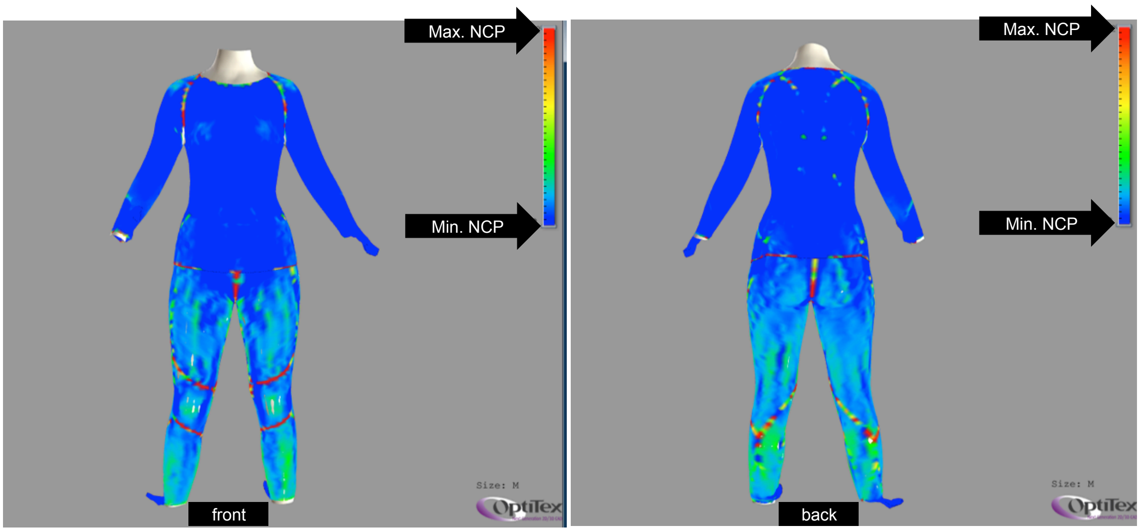




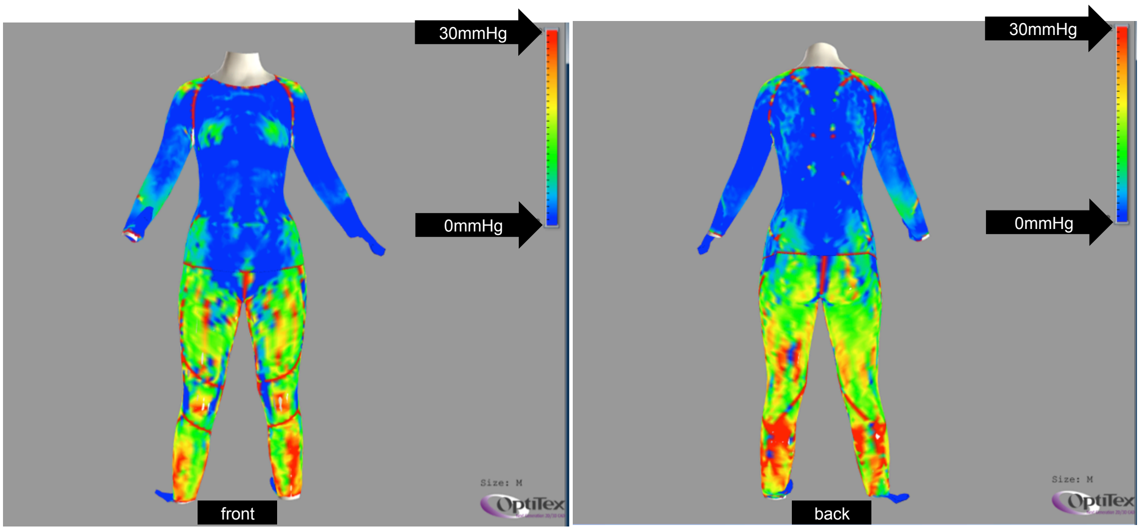
17FA25 – S-M - Normal collision pressure set as max. 30mmHg:



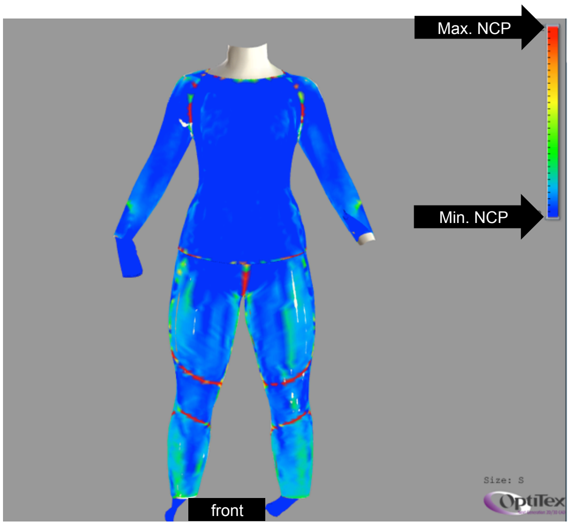
25FA28 – S-M - Normal collision map:

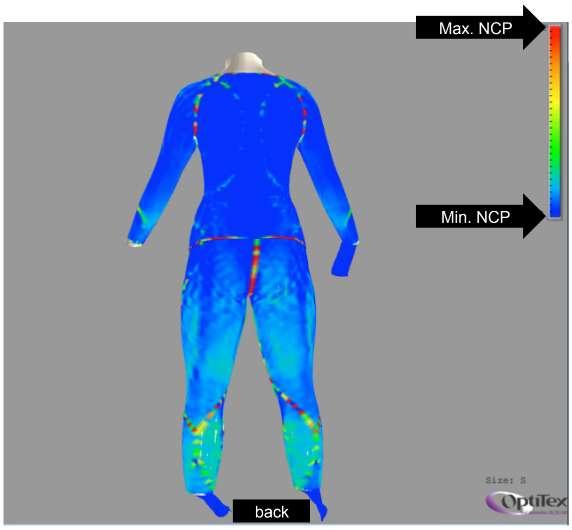


25FA28 – S-M - Normal collision pressure set as max. 30mmHg:

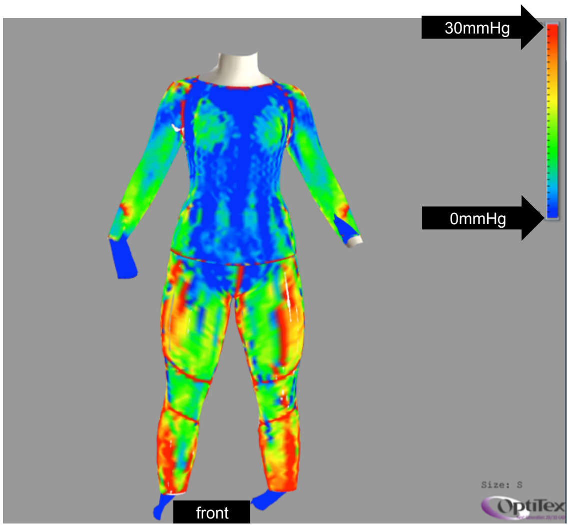


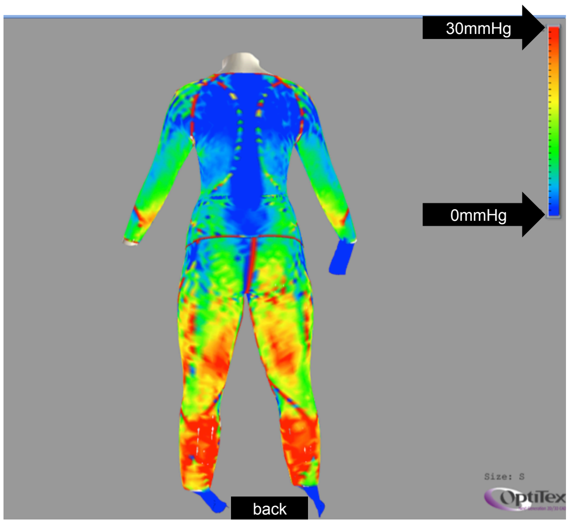
26FR22 – S-S - Normal collision map:



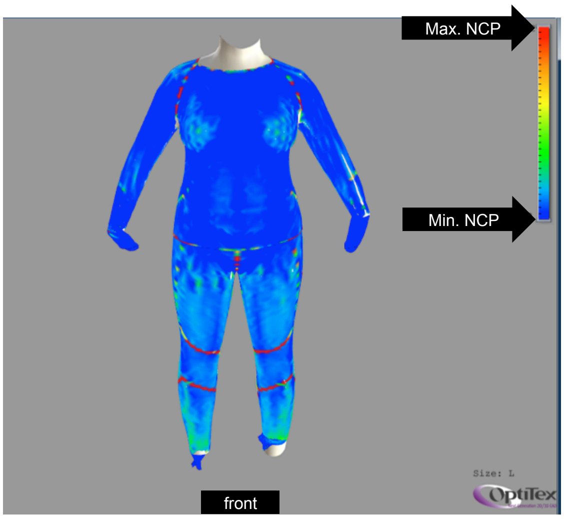


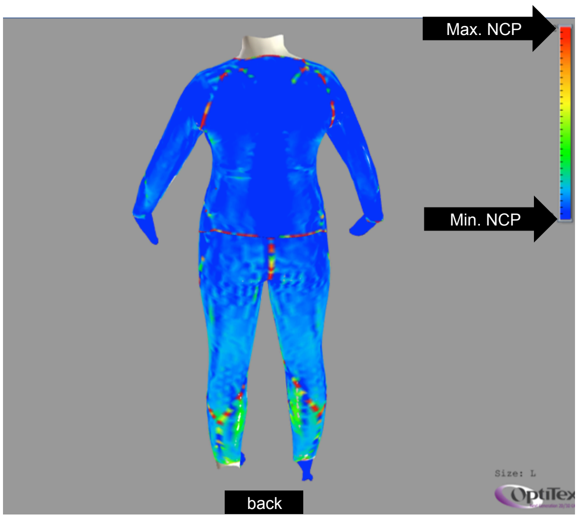
26FR22 – S-S - Normal collision pressure set as max. 30mmHg:



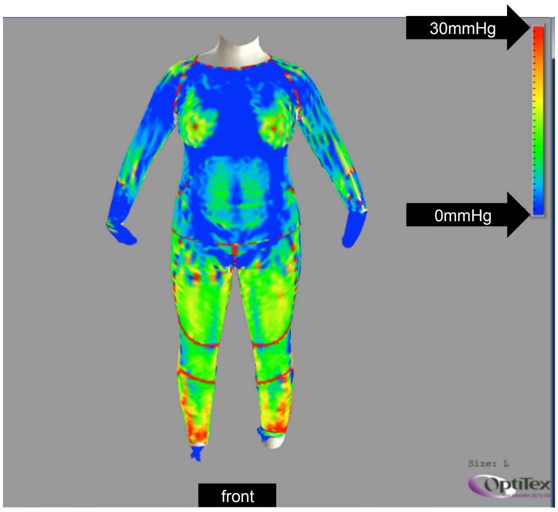


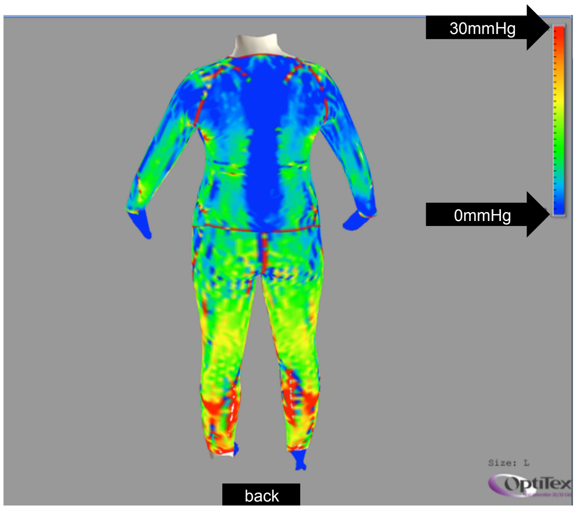
27FA47 – M-L - Normal collision map:



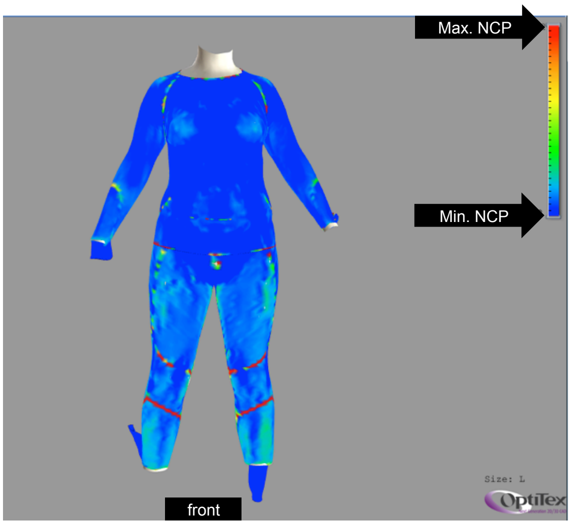


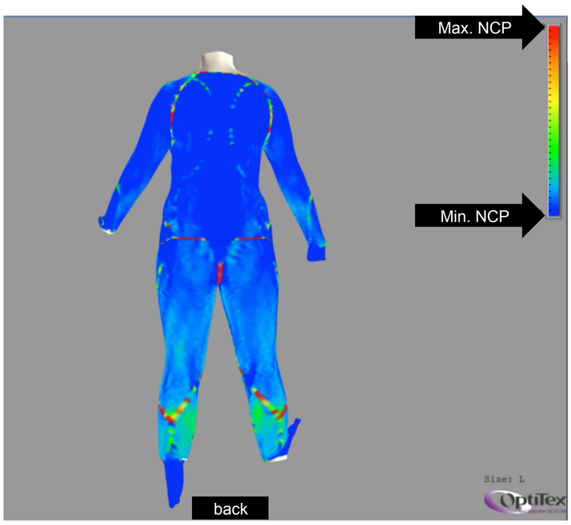
27FA47 – M-L - Normal collision pressure set as max. 30mmHg:



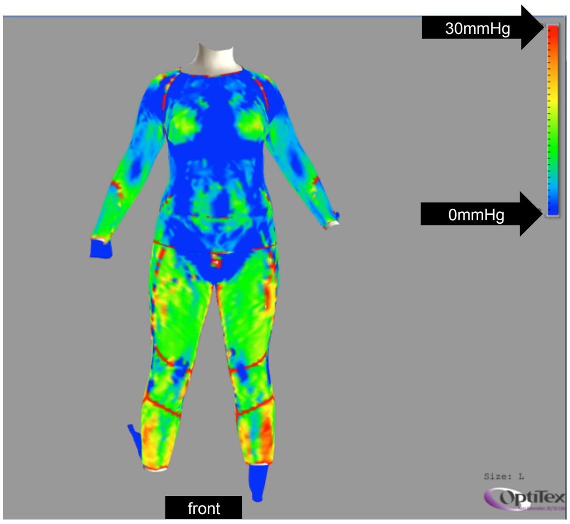


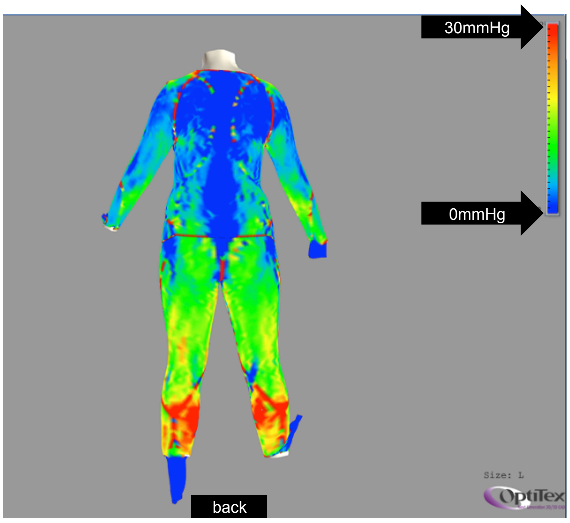
31FA46 – M-L - Normal collision map:



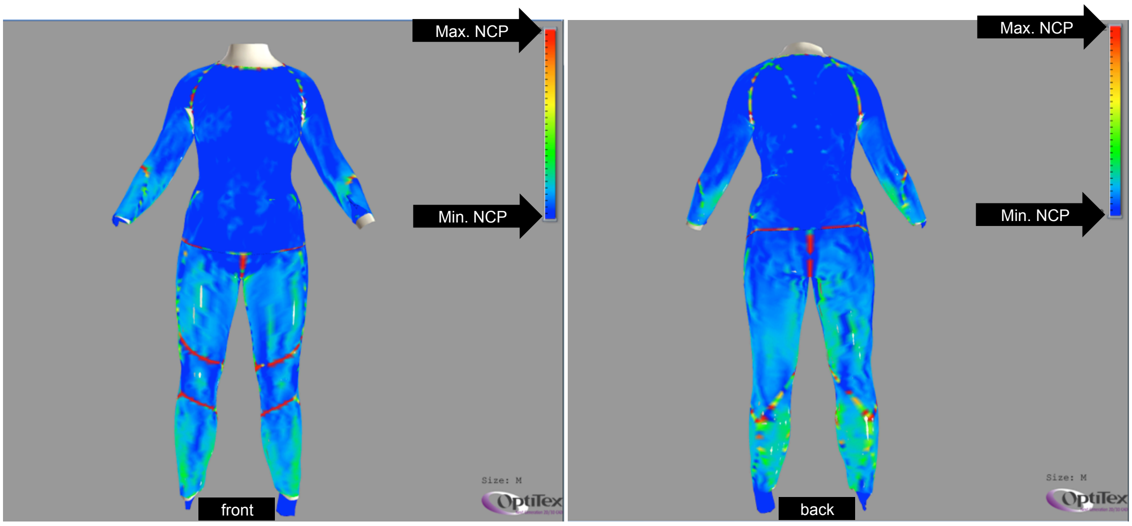


31FA46 – M-L - Normal collision pressure set as max. 30mmHg:

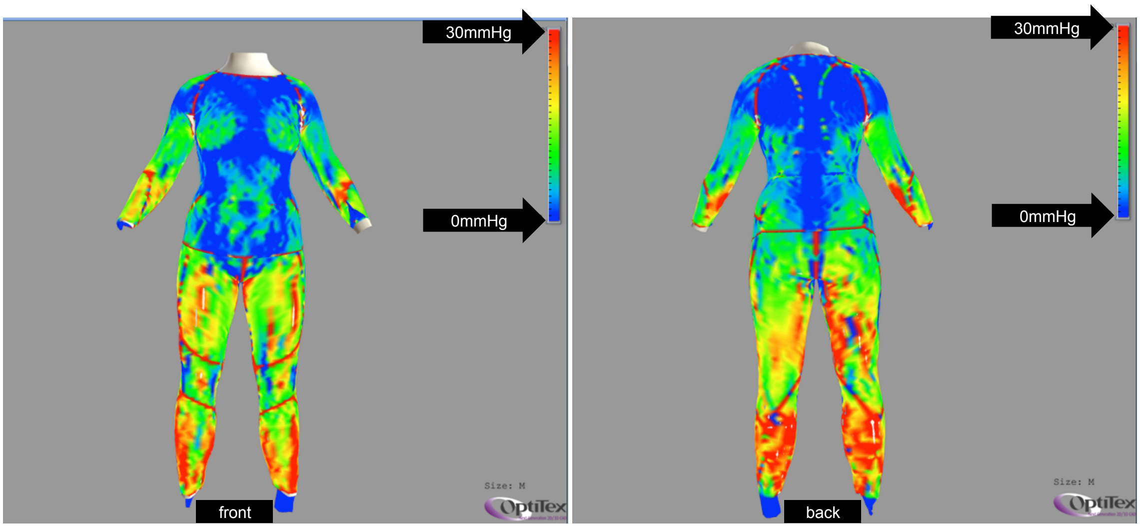




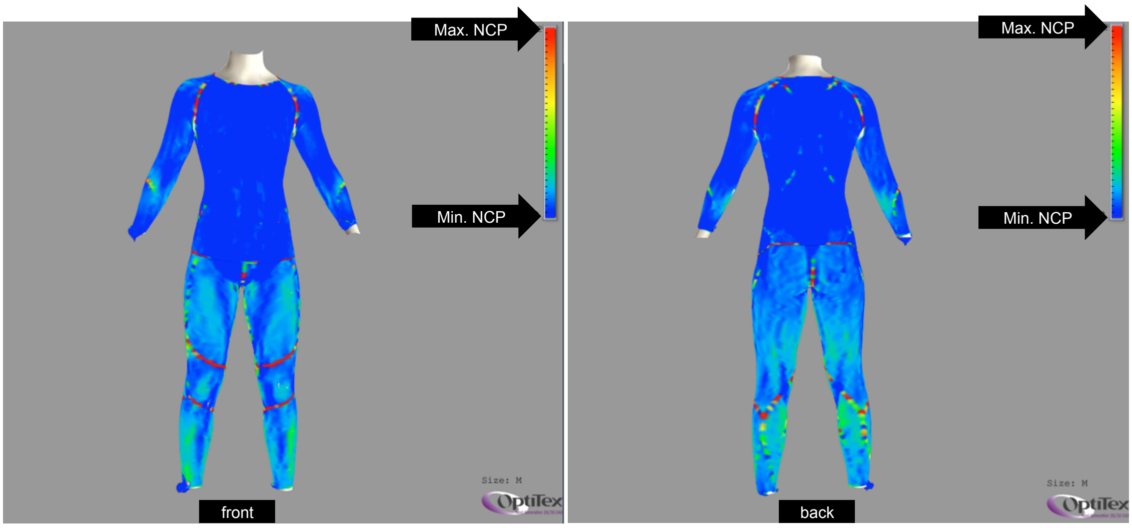
32FA34 – S-M - Normal collision map:



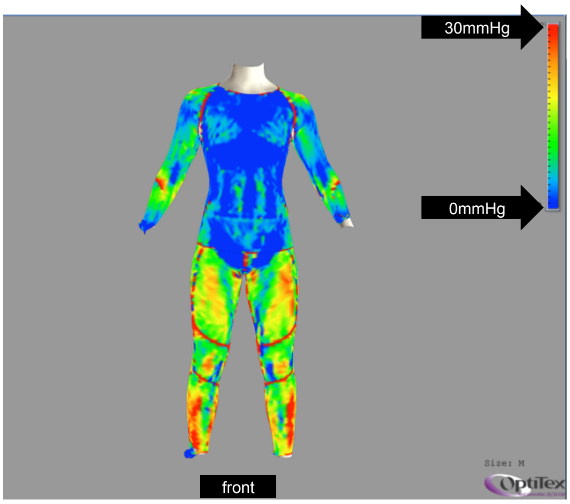
32FA34 – S-M - Normal collision pressure set as max. 30mmHg:

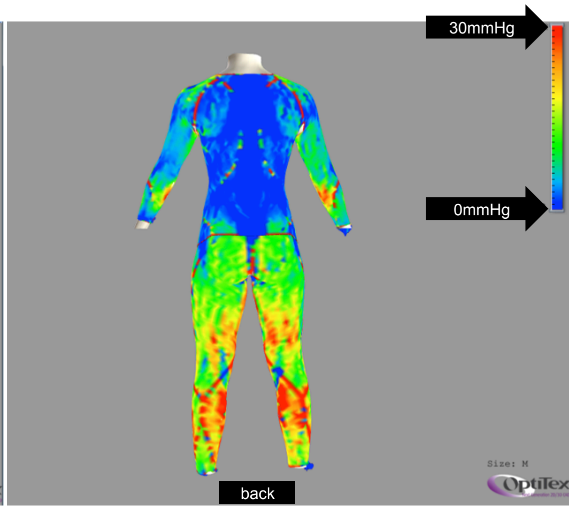


35FA30 – S-M - Normal collision map:

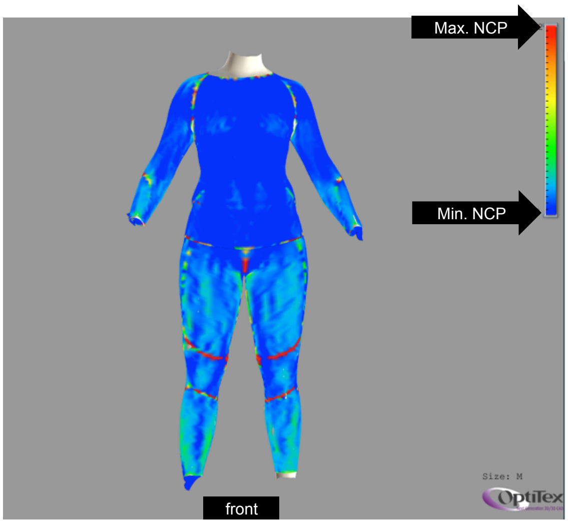


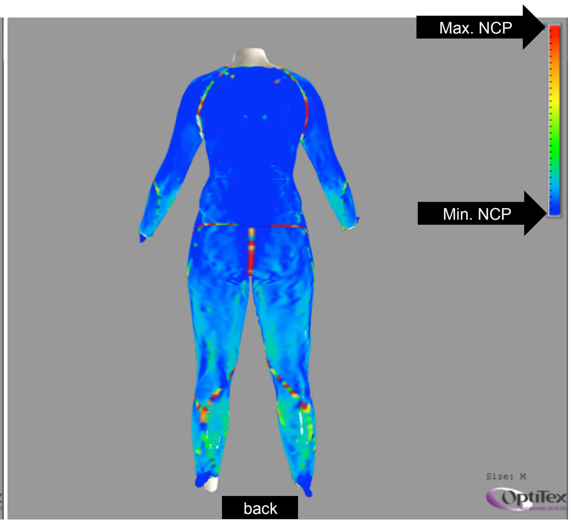
35FA30 – S-M - Normal collision pressure set as max. 30mmHg:



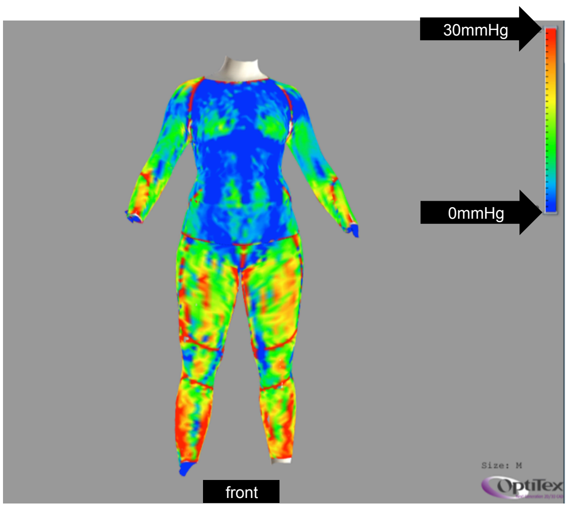


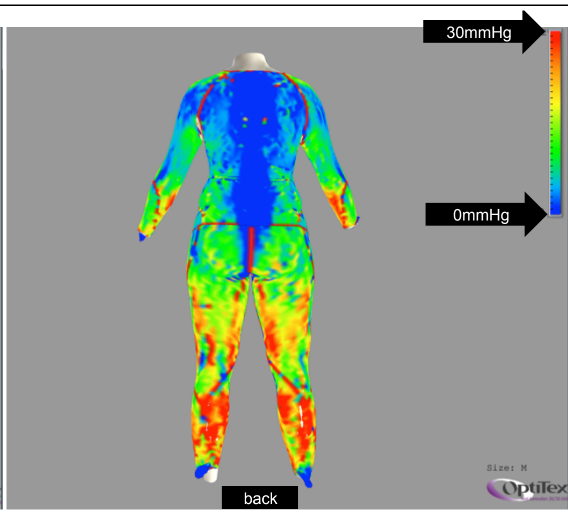
37FZ33 – S-M - Normal collision map:



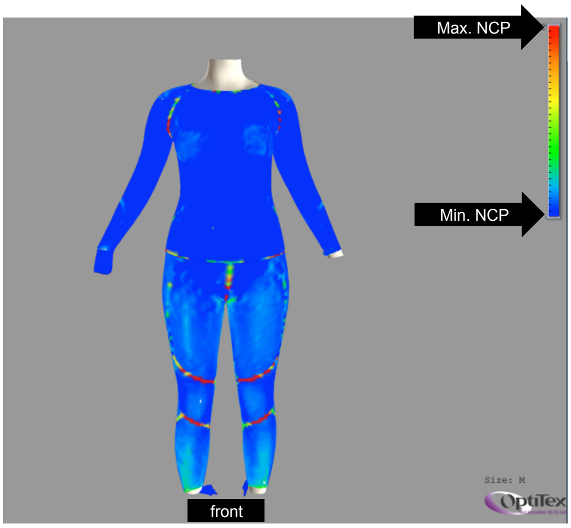


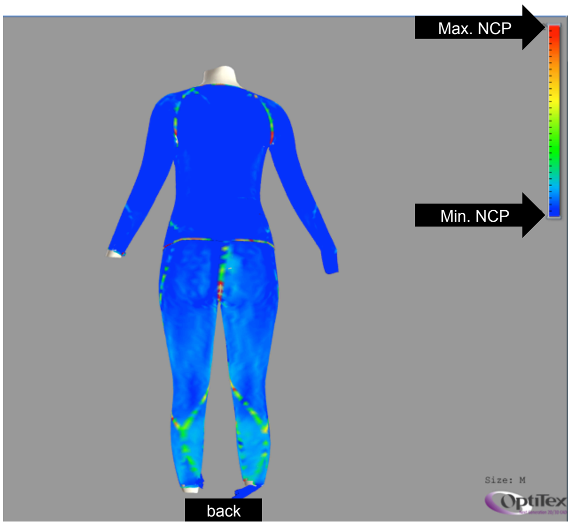
37FZ33 – S-M - Normal collision pressure set as max. 30mmHg:



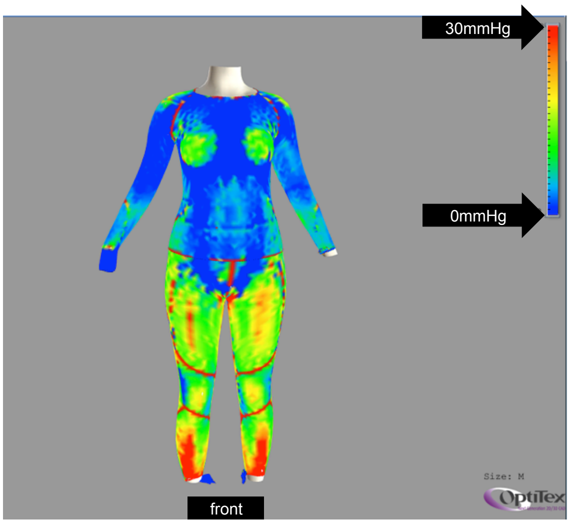


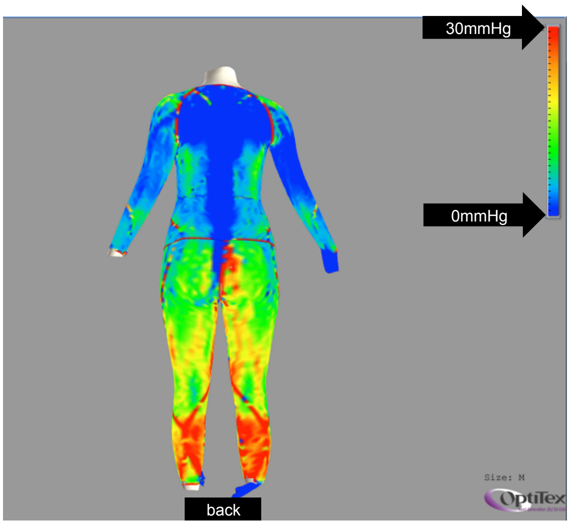
A013FA25 – S-M - Normal collision map:



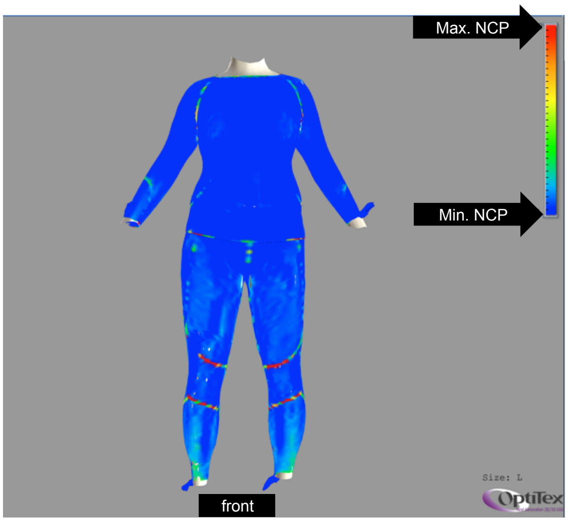


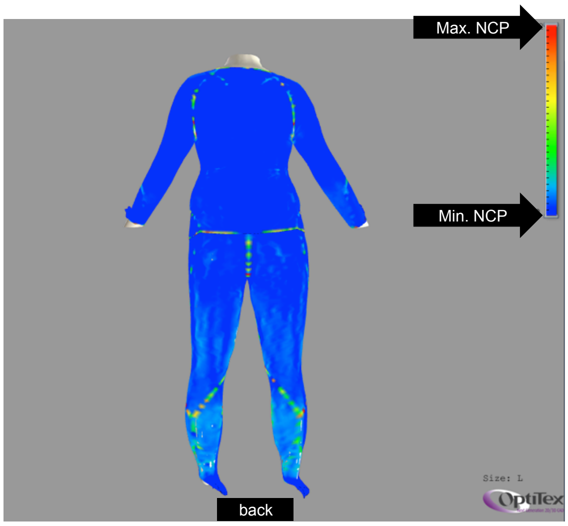
A013FA25 – S-M - Normal collision pressure set as max. 30mmHg:



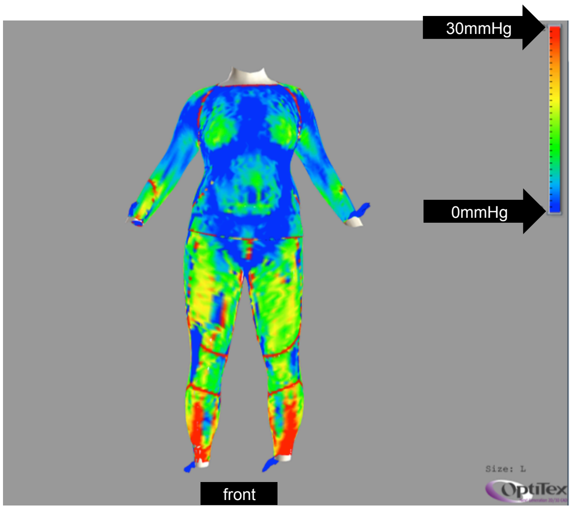


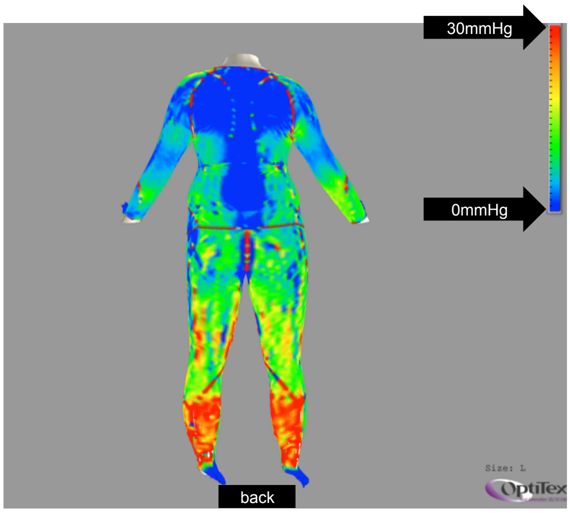
A024FA23 – M-L - Normal collision map:



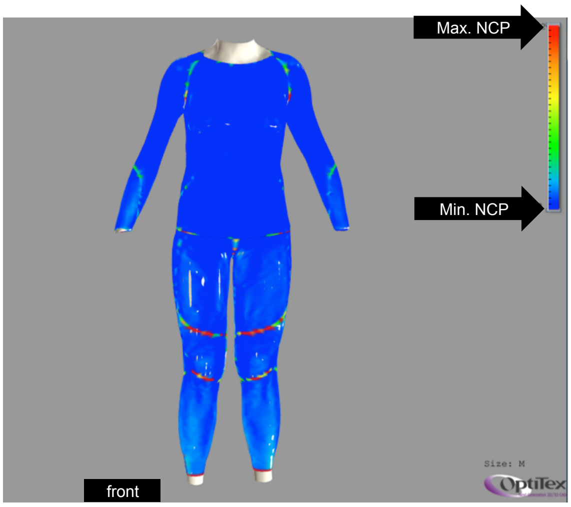


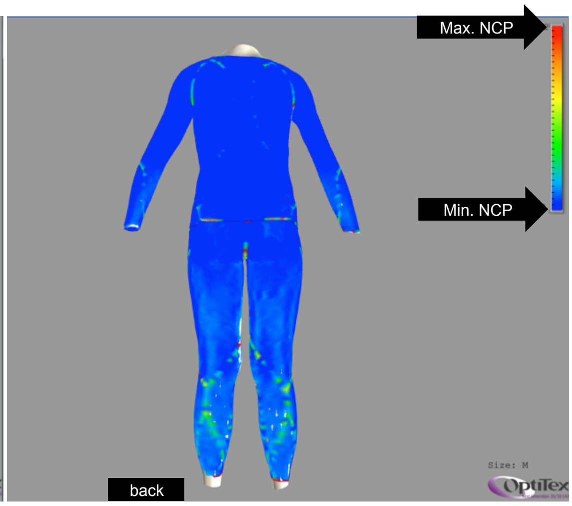
A024FA23 – M-L - Normal collision pressure set as max. 30mmHg:



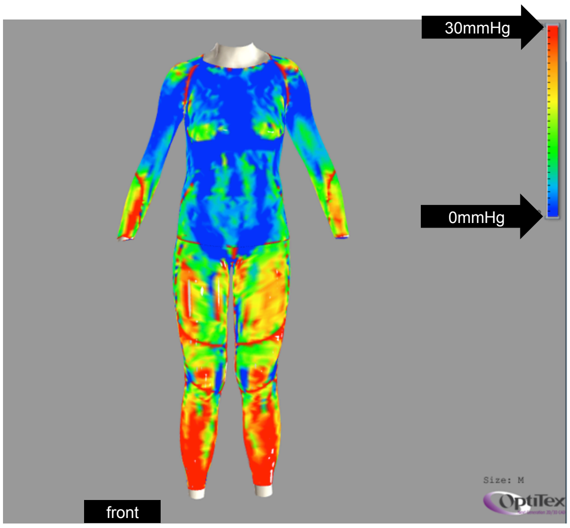


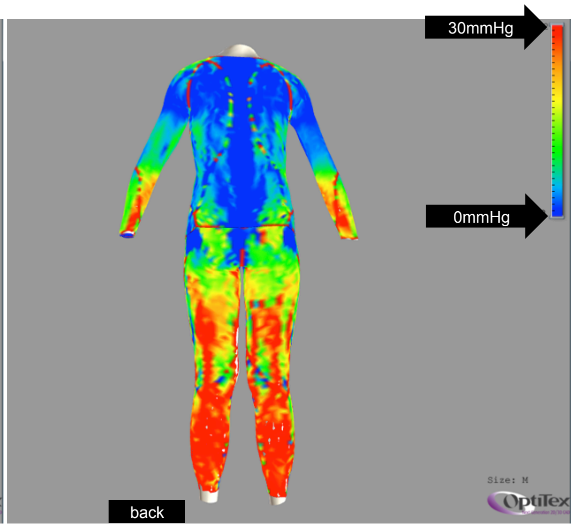
A194FA40 – S-M - Normal collision map:



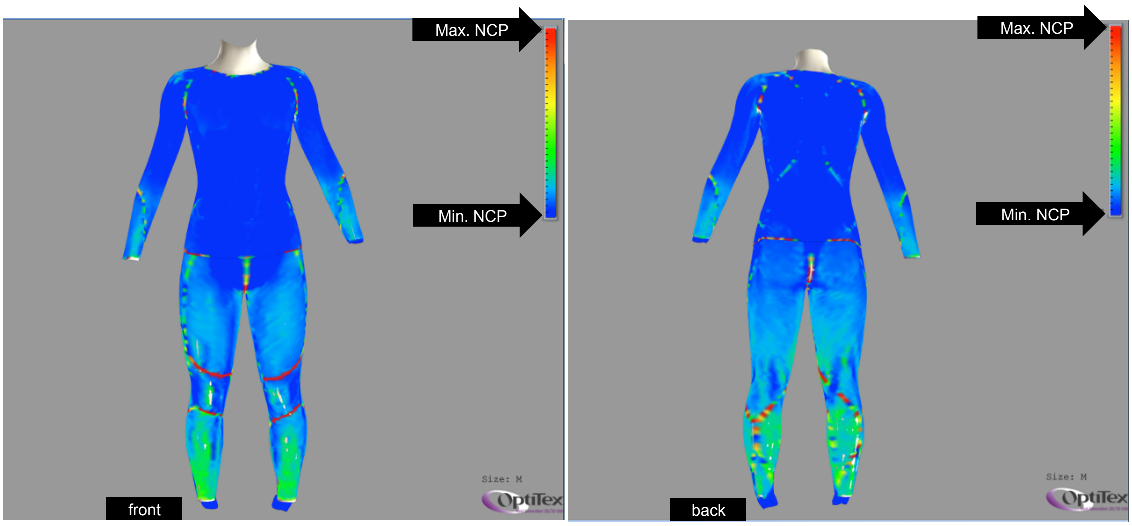


A194FA40 – S-M - Normal collision pressure set as max. 30mmHg:

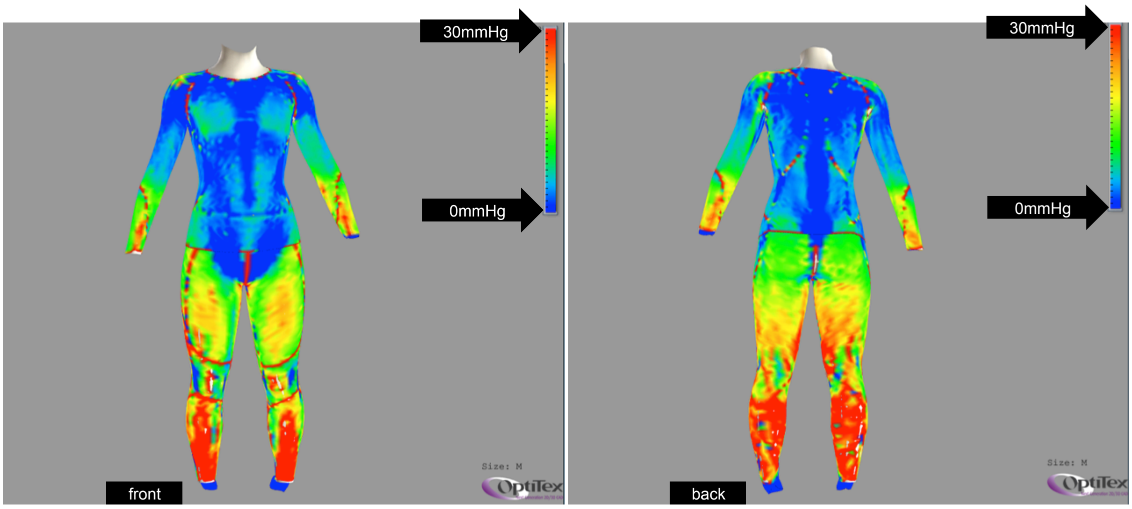




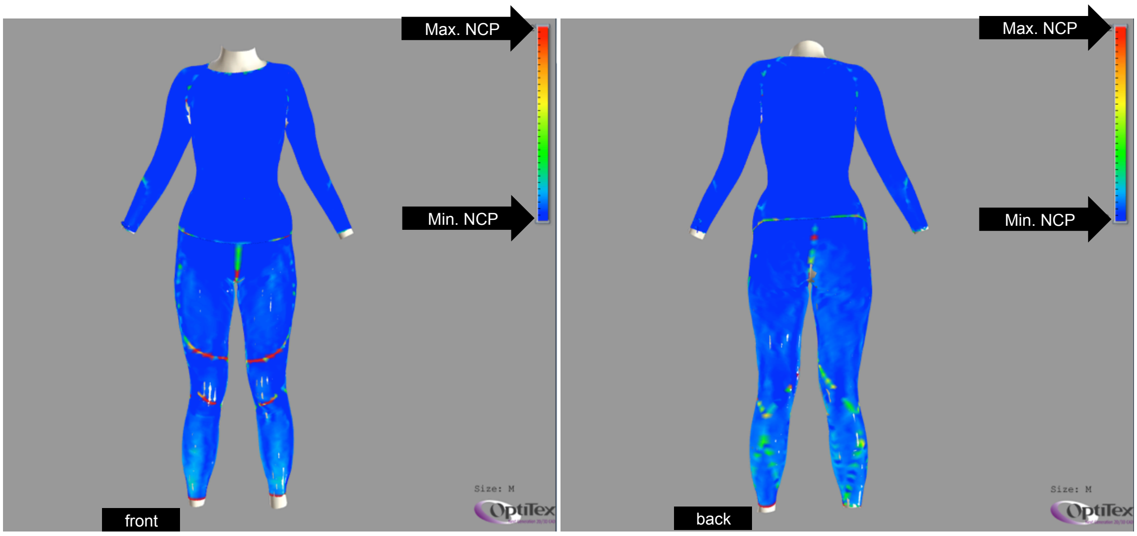
A476FA22 – S-M - Normal collision map:



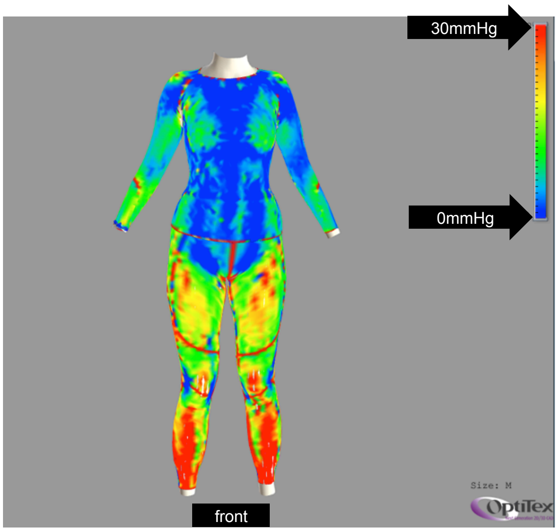
A476FA22 – S-M - Normal collision pressure set as max. 30mmHg:

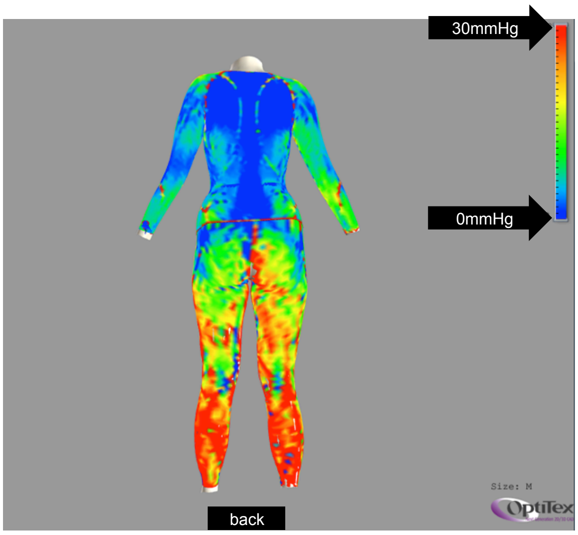


A530FA24 – S-M - Normal collision map:



A530FA24 – S-M - Normal collision pressure set as max. 30mmHg:





Appendix SS. Results of virtual pressure analysis

Appendix Table SS-1: Wilcoxon signed-rank test: Differences in NCP for simulation settings A and B

Pressure Measurement Location	*Z*	*p*	*r*
B31	-3.18	0.001*	-0.88
B41	-0.73	0.463	-0.20
B51	-0.31	0.753	-0.09
B61	-1.50	0.133	-0.42
B71	-0.94	0.345	-0.26
B91	-1.36	0.173	-0.38
T11	-1.36	0.173	-0.38
T21	-1.78	0.075	-0.49
T31	-0.38	0.701	-0.11
T41	-0.77	0.442	-0.21
T51	-1.78	0.075	-0.49
T91	-1.71	0.087	-0.47
T111	-0.87	0.382	-0.24
T121	-0.04	0.972	-0.01

*significant difference ($p < 0.01$)

Appendix Table SS-2: Wilcoxon signed-rank test: Differences in virtual tension for simulation settings A and B

Pressure Measurement Location	*Z*	*p*	*r*
B31	-2.55	0.011**	-0.71
B41	-2.76	0.006*	-0.77
B51	-1.29	0.196	-0.36
B61	-3.18	0.001*	-0.88
B71	-0.66	0.507	-0.18
B91	-3.11	0.002*	-0.86
T11	-2.41	0.016**	-0.67
T21	-1.71	0.087	-0.48
T31	-1.85	0.064	-0.51
T41	-0.31	0.753	-0.09
T51	-3.18	0.001*	-0.88
T91	-2.83	0.005*	-0.78
T111	-0.38	0.701	-0.11
T121	-1.15	0.249	-0.32

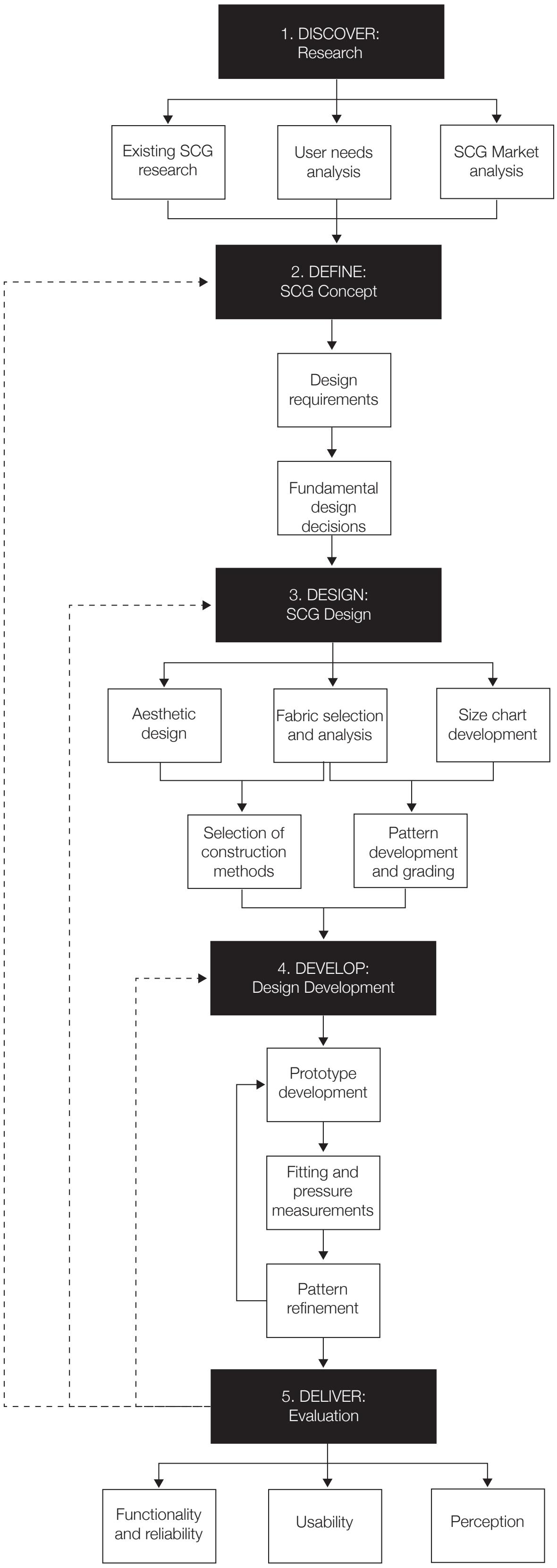
*significant difference ($p < 0.01$)
**significant difference ($p < 0.05$)

Appendix Table SS-3: Wilcoxon signed-rank test: Differences between in vivo pressure and NCP

Pressure Measurement Location	Simulation Setting	*Z*	*p*	*r*
B31	A	-3.18	0.001*	-0.88
	B	-3.18	0.001*	-0.88
B41	A	-3.18	0.001*	-0.88
	B	-3.18	0.001*	-0.88
B51	A	-3.18	0.001*	-0.88
	B	-3.18	0.001*	-0.88
B61	A	-3.18	0.001*	-0.88
	B	-3.18	0.001*	-0.88
B71	A	-2.41	0.016**	-0.67
	B	-2.69	0.007*	-0.75
B91	A	-3.18	0.001*	-0.88
	B	-3.11	0.002*	-0.86
T11	A	-1.64	0.101	-0.46
	B	-1.78	0.075	-0.49
T21	A	-0.45	0.650	-0.13
	B	-1.64	0.100	-0.46
T31	A	-0.18	0.861	-0.05
	B	-0.31	0.753	-0.09
T41	A	-1.64	0.101	-0.46
	B	-0.87	0.382	-0.24
T51	A	-1.41	0.158	-0.39
	B	-0.25	0.807	-0.07
T91	A	-2.83	0.005*	-0.78
	B	-2.48	0.013**	-0.69
T111	A	-1.85	0.064	-0.51
	B	-1.71	0.087	-0.47
T121	A	-1.08	0.279	-0.30
	B	-1.22	0.221	-0.34

*significant difference ($p < 0.01$)
**significant difference ($p < 0.05$)

Appendix TT. Sports Compression Garment Design Process



Appendix Figure TT-1: Detailed Sports Compression Garment Design Process