The Application of Auxetic Structures for Rugby Shoulder Padding

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PhD 2021

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A thesis submitted in partial fulfilment of the requirements of the Manchester Metropolitan University for the degree of Doctor of Philosophy

Manchester Fashion Institute

Faculty of Arts and Humanities

Manchester Metropolitan University

2021

Abstract

Auxetic materials have a negative Poisson's ratio (NPR), they laterally expand under stretch, laterally shrink under compression and conform to curved surfaces through the formation of synclastic curvature. It was identified that these qualities could enhance the current standard of personal protective equipment (PPE) often embedded within sports apparel (sPPE) at regions of the body exposed to soft tissue injury through collision, fall or impact. Current pads can inhibit movement, breathability and wicking, whilst moulded pads are prone to saddling; segmentation techniques including vacuum moulding and cut segmenting are applied to improve the conformability of padding. It is unclear as to whether the impact performance of auxetic sPPE is affected under a state of synclastic curvature or biaxial expansion and as such sPPE applications are limited to date. User-centred design strategies for functional clothing have not yet been established for sPPE with auxetic elements, this could improve accessibility for implementation by pad designers. Therefore, this research set out to determine strategies for the application of auxetic sPPE with enhanced conformability.

In order to achieve the overall aims of this research a multi-method research strategy was employed investigating the problem first through the user and product. A quantitative survey was designed to assess user perceptions of commercial rugby shoulder padding comfort. Commercial rugby shoulder padding featuring different segmentation types were assessed for conformability to the shoulder region through fit and pressure comfort measurements. Following this the research investigated how auxetic structures of different geometries could enhance the conformability of rugby shoulder padding. Data collection included pressure comfort assessments, impact tests over curved surfaces and lateral expansion of pads through tensile displacement and fitting pads to a mannequin.

A user-perception survey of commercial rugby shoulder pads found that fit and protection were the most important of six realms of respondents perceived comfort.

Current regulations for rugby shoulder padding suggest that pads must not hinder comfort and mobility yet only stipulate test methods for impact protection. The commercial rugby pads provided poor pressure comfort and conformability across the different types of segmentation and segment (unit cell) shapes. It was also identified that poor conformability was of detriment to product function where pads moved out of position. The findings from the survey and product analysis showed that the main cause of poor fit and pressure comfort was padding bulkiness caused by larger circumferences and less conforming segmentation techniques. Cut-segmented pads provided the best route to conformability but none of the pads provided the ideal pressure comfort range identified for this research.

Rugby shoulder pads were cut-segmented with different auxetic structures and following this manipulation of an auxetic geometry was investigated. It was found that sPPE with auxetic elements conformed to curvatures and expanded laterally compared to the non-auxetic alternative. Parameters for use were identified including that opening consistency of the individual auxetic geometries had potential to affect sPPE function. Auxetic geometries in an arrangement of singular cuts had the most consistent opening mechanism throughout the pad when subject to a tensile load. Additionally, the manipulation of an auxetic geometry showed that anisotropy can be applied to offer higher displacement in specific directions, which may have use for sPPE not subject to rotational forces such as knee pads. It was also found that increasing the difference between rib (unit cell wall) length and separation between ribs led to the auxetic structure opening out less, which could be applied at specific regions of a pad that require restriction.

The findings of this research showed that auxetic structures could be manipulated for different sPPE applications. A recommended strategy for development of sPPE with auxetic elements was presented, influenced by user-centred design strategies. The first stage of the strategy focused on defining the problem via the user, sport, body region and product. Ideation of possible solutions formed the second stage, by assessing manipulations of auxetic geometry in relation to requirements of the user, product, sport and body region, and was repeated until the product was found to provide a solution to the defined problem; implementation completed stage 3.

Acknowledgements

This research has benefited from the expertise and guidance of an interdisciplinary team across textile technology, material science and sports engineering. I wish to extend a tremendous thank you to Dr Tasneem Sabir, Dr Tom Allen and Professor Andrew Alderson for their expertise and supervision.

The two main topics in this research, auxetic structures and personal protective equipment for sportswear have formed a fascinating challenge. Investigation of these topics has received exceptional support from current and former PhD students Syed Adil Imam, Dr Chloe Newton-Mann and Todd Shepherd of Manchester Metropolitan University as well as Dr Oliver Duncan of Sheffield Hallam University. Training from the Manchester School of Sociology, Fashion Institute and School of Engineering have been invaluable toward the completion of the study including guidance from Praburaj Venkatraman and Mike Green. Technicians of the Manchester Fashion Institute Derek Hebdon and Jayne Gill deserve special thanks for their assistance in the Textile lab and with conducting body scans, respectively.

Funding from the Manchester Fashion Institute was gratefully received for the purchase of the commercial rugby pads assessed in this study. I am also like to express my appreciation for the Vice Chancellor studentship that enabled me to undertake this study.

The friendly faces of the Postgraduate Arts and Humanities Centre have provided endless companionship and support throughout the course of this study.

Publications

The research involved in this PhD has been disseminated at The 91st Textile Institute World Conference 2018, the 12th Biennial Conference on the International Sports Engineering Association 2018 and the 9th International Conference on Auxetics 2018. The research has been published in the following articles:

Duncan, O., Shepherd, T., Moroney, C., Foster, L., Venkatraman, P. D., Winwood, K., Allen, T., and Alderson, A. (2018a) ‘Review of auxetic materials for sports applications: expanding options in comfort and protection.’ *Applied Sciences*, 8(941), pp. 1-33.

Moroney, C., Alderson, A., Allen, T., Sanami, M., Venkatraman, P. D. (2018) ‘The application of auxetic material for protective sports apparel.’ *Proceedings*, 2(6), 251.

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Glossary of Terms

3D printing: Fabricating materials through additive manufacturing

3D: Three-dimensional

3-Pointed star auxetic structure: Its geometrical arrangement produces 6-sided unit cells

4-Pointed star auxetic structure: Its geometrical arrangement produces 8-sided unit cells

Anisotropic: auxetic structures: Poisson's ratio has more than one value

Auxetic: Structures or materials exhibiting negative Poisson's ratio

Auxetic closed cell foam: A conventional closed cell foam which has been converted to have auxetic characteristics through a process of steam penetration

Auxetic open cell foam: A conventional open-cell foam which has been converted to have auxetic characteristics through a heating and compression process which inverts its cell ribs

Auxetic structure: Unlike conventional structures, these enable lateral deformation under tensile axial loading due to exhibiting negative Poisson's ratio

Ballistics PPE: Relative to impacts caused by projectiles and firearms

Biaxial expansion: Ability to laterally expand under stretch and laterally shrink under compression

Chiral auxetic structure: Its geometrical arrangement produces 6-sided unit cells

Conformability: Consistent in form and characteristics

Consistent opening mechanism: Unit cells opening or closing equally throughout the network of auxetic structures when subject to tension or compression

Geometry: Arrangement of ribs within a unit cell

Gradient auxetic structure: Structure with regions that are both auxetic and non-auxetic

Impact: The action of energy transferring between surfaces or objects due to coming into forcible contact

Impact protection: Ability to transfer energies from an impact or collision into tolerable forces for the body.

In-plane auxetic structure: Exhibiting negative Poisson's ratio through the x and y axis

Isotropic auxetic structures: Poisson's ratio has one value

NPR: Negative Poisson's Ratio

Opening mechanism: Enlarging and closing of unit cells within a network of auxetic structures under tension and compression

PPE: Personal Protective Equipment

Rib: One side or edge of a unit cell

Rotating squares auxetic structure: Its geometrical arrangement produces 4-sided unit cells

sPPE: Personal Protective Equipment for Sportswear

Synclastic curvature: Excellent shape fitting ability to curved surfaces due to an upper surface biaxially expanding and a lower surface biaxially contracting

Through-the-thickness auxetic structure: Exhibiting negative Poisson's ratio through the x, y and z axis

Uniaxial: Relating to a single axis

Unit cell: A singular structure that may belong to a larger network of unit cells

User-centred design: each phase of product design and development focuses on the user and their needs

1 Introduction

1.1 Research Background and Rationale

The sportswear market has grown in recent years (Sanchez et al., 2020), across all segments including protective garments, coinciding with a growth in sporting participation (Sport England, 2020). The Active Lives Adult Survey November 2018/2019 by Sport England (2020) reported a record high of 28.6 million adults participating in at least 150 minutes of moderate intensity physical activity a week. Personal Protective Equipment for sportswear (sPPE) must utilise the thinnest possible padding to prevent restriction of athletic performance. However, padded materials worn for impact and collision sports can inhibit movement, breathability and wicking, whilst moulded pads are prone to saddling (Venkatraman and Tyler, 2016). Therefore, there are limitations even to the market leaders in impact protection, despite market growth.

sPPE encompasses design solutions to cushion and soften blows (Watkins and Dunne, 2015) encountered during impact and collision sports which encompass injury risks (BCIRPU, 2013). The soft pads embedded in sportswear across many contact sports have been found to bottom out under high impact force (Beer and Bhatia, 2009), meaning that thickness of padding diminishes under higher impact loads. Such materials are considered to offer a restrictive fit (Tsui, 2011) due to having poor conformability (Griffiths, 2009). Fit issues can cause some sporting participants to sacrifice protection in place of comfort as has been identified for rugby sPPE excluding body padding (Finch et al., 2001). There are sport specific bodies which govern the design regulations for corresponding sPPE, including World Rugby (2019b) which focuses on impact protection.

The design of sPPE must meet the requirements of the respective sporting body as well as the user’s physiological and psychological needs (Suh et al., 2010). As such, typically a user-centre design approach is required (Watkins and Dunne, 2014) in the development of sPPE. Developing sPPE with auxetic elements has been recommended by some authors, due to having a negative Poisson's ratio (NPR) (Lisiecki et al., 2013; Allen et al., 2015). Unlike conventional materials, the potential application for sPPE with NPR is owed to the ability for these pads to laterally expand under tensile displacement (Martin, 2011; Cross et al., 2015) and conform to domed surfaces. However, at present a user-centred design strategy for sPPE with auxetic elements is yet to be produced.

The ability for auxetic structures to open out laterally and conform to domed surfaces offers potential to expand with stretch sPPE garments and conform to the body. Conversely, current sPPE is comprised of rigid, non-stretch materials joined to stretch fabrics, which are fitted to curved body regions such as the shoulder, which are subject to a range of movements. The reason that auxetic structures have these desirable characteristics is due to the geometry of its internal unit cell structure (Ashby et al., 1995). Under tension and compression the unit cell is able to open out and close, respectively (Sanami et al., 2014a). When subject to extension in one direction, the unit cell opens out, becoming wider in the direction of the applied force as well as the perpendicular direction, in which a conventional structure would become thinner. In the same way, when an auxetic unit cell is compressed in one direction, it appears thinned in the perpendicular too, where as a conventional structure would become thicker in the perpendicular.

Auxetics are considered an emerging class of material (Wong et al., 2019) and although already found to occur in nature (Farrell et al., 2020), more examples continue to be discovered. Examples of natural auxetic materials include salamander (Frolich et al., 2009) and cow teat skin (Lees et al., 1991). In 1987 the first man made auxetic material was developed, in the form of auxetic foam by Lakes (1987). Uses for auxetic structures have been slow until recent years. The number of patents filed for auxetic applications shows a greater increase since the millennium (Toronjo, 2013; Cross et al., 2015).

The auxetic effect enables a route to attaining extreme values of particular properties in comparison to conventional materials with positive Poisson's ratio (Yao, 2016). This anomalous behaviour can provide fracture toughness, synclastic curvature under pure bending (Choi and Lakes, 1992), indentation resistance (Lakes and Elms, 1993; Chan and Evans, 1998), shear resistance (Choi and Lakes, 1992) and vibration damping (Howell et al., 1991; Chen and Lakes, 1996). However, uses of auxetic materials remain limited to date and Goud (2010) suggests that these are unlikely to be deliberately used for the auxetic effect itself. The application of auxetic materials has been limited because of problems with deploying these materials in their fabricated forms (Ugbolue et al., 2012); as such, previous research has neglected to take a user-centred approach. Therefore, to improve the potential for commercial applications, this research investigates how auxetic structures can be manipulated for sPPE to provide enhanced conformability to body curvature and movement.

1.2 sPPE Overview

sPPE includes headwear, for sports in which impact occurs from hard objects travelling at speed such as a cricket ball (Klossner, 2013). In games such as rugby, hockey and lacrosse, mouth guards are worn as a preventative method where there is chance of dental trauma. Shin pads are worn to prevent the shin from receiving fractures, sprains, bruising and swelling, they are worn in many sports including football and hockey. Finally, shoulder pads provide protection in games where the player's shoulder is likely to come into contact with the ground or other players; sPPE materials differ in hardness depending on the nature of the sport. Despite this wide variety and the injury risks involved, due to the culture of certain sports and other factors relating to comfort, many participants choose not to wear sPPE (Finch et al., 2001).

Venkatraman and Tyler (2016) have compared sPPE padded materials, including D30, GPhlex, Poron XRD, EVA foam and leather; for which the former reduced peak forces. D30 is applied for sPPE across American football, snowboarding, mountain biking and running to name a few, providing low profile head, limb and footwear protection. D30 locks under impact energies, which would become hard and hazardous to the opposing player in a contact sport such as rugby. Ethylene vinyl acetate (EVA) foam is a cross-linked closed cell foam material frequently used for rugby body padding, designed to be soft, with a rubber like texture and with good shape recovery after deformation. Even though EVA is the market leader in rugby body padding, at slimmer thicknesses it behaves similar to leather under impact. Therefore, impact protection involves compromises in the design of sPPE.

1.3 Potential and Development of Auxetic sPPE

The novelty of this research is challenged by the sportswear industries interest in auxetic materials and the rapid rate at which the fashion and textiles industries are able to develop and innovate new products. The world's leading trend company, WGSN, first reported on auxetics in 2011 and auxetic yarns were highlighted as having potential for blast protection in firefighters' uniforms; reports were made again in 2014, 2017 and 2018, with a new focus on sportswear. Current applications for auxetic structures in trainer soles by Nike (Cross et al., 2015) and Under Armour (Toronjo, 2013) as well as a helmet liner for the D30 (2018) trust helmet pad system, for which the auxetic effect is applied in-plane. Conversely, applied through-the-thickness, NPR can be exhibited in three-dimensions (Zhao et al., 2019) but benefits of current sportswear applications are described by brands, assessments of the effectiveness have not been published.

In contrast to the commercial outputs for auxetic sPPE, auxetic research often focuses on the development of NPR materials with recommendations for further development towards potential applications. sPPE exhibiting in-plane NPR can be produced in different ways including through cut-segmentation. This technique is used commercially for sPPE segmentation (Morrow and Winningham, 2006; Gordon et al., 2015) that includes rugby shoulder padding. Therefore, cut-segmentation is a readily available route for investigating the parameters of auxetic structures applied in-plane for sPPE.

1.4 Significance of the Research

This research investigates the potential of sPPE with auxetic elements from an apparel perspective, as the effect of synclastic curvature and lateral expansion on product function are unknown. In addition, there are gaps in knowledge of how segmenting, embedding or joining body padding to stretch fabrics affect fit and conformability to body curvatures and movements. Current knowledge of auxetics is critically analysed first, to determine how far it may influence the materials and methods utilised in this research. Issues with current sPPE design are investigated critically also, in order to validate the scope to innovate the current standard with auxetic structures.

1.5 Research Aim

This research aims to analyse the optimum level of parameters for the design and fabrication of auxetic sPPE. The project will have a focus on the potential for garment application and as such analysis will relate to fit through conformability and synclastic curvature of the sPPE. This overriding aim will be met with the following objectives:

Objective 1: To critically evaluate literature pertaining to garment technology and wearer issues in padded sportswear and identify suitable auxetic structures and fabrication methods for application as sPPE.

Objective 2: To analyse commercial rugby shoulder padding in relation to the comfort requirements of sporting participants.

Objective 3: To apply auxetic patterns to sPPE through cut-segmentation and evaluate the effectiveness of the developed auxetic sPPE through impact tests under synclastic curvature and analyse pressure comfort and lateral expansion.

Objective 4: To determine design parameters for the most suitable auxetic impact protective material (identified through Aim 3), through manipulating scale, gradient and shape.

1.6 Predicted Impact of the Research

This research presents a novel approach in researching the application of different auxetic geometries as sPPE segmentation. The research is motivated by reports of user comfort issues and poor conformability across the sPPE market combined with reports that auxetic structures could lead to an enhanced solution. Previous research of auxetic structures for sPPE applications do not investigate geometric effects of these structures on product functions especially relating to comfort. Additionally, publications have not integrated product users or body regions within assessments of the effectiveness of developed structures. Therefore, this research will outline the parameters for developing and designing sPPE with auxetic structures. The expected outcome will inform future pad design and auxetic research for how auxetic structures can be used to enhance pad conformability and in turn encourage product uptake for body padding across different sports.

1.7 Thesis Structure

The contents of this thesis comprise of six chapters. The parameters of this research are built on the gap revealed by the literature review of current research in Chapter 2. This literature review is divided into two main themes, i) the current standard of protective materials and ii) sPPE auxetic structures and fabrication methods. The findings of Chapter 2 serve as a database for knowledge of auxetics and issues with protective apparel. The findings informed the research methods employed in the following chapter.

The primary research methods and findings are divided into three phases in Chapters 3, 4 and 5. Chapter three outlines the research perspectives and methodologies as well as the strategies for conducting the study. Following this, Chapter 4 presents the results of the study which are then discussed in Chapter 5 in synthesis with the findings from Chapter 2. The outcome of Chapter 5 is a strategy for designing sPPE with auxetic structures for enhanced conformability. Finally, chapter 6 summarises the main findings of this thesis and indicates directions for future research.

Chapter 2

2 Literature Review

Introduction

The literature review critically assessed research of auxetic structures and the potential application as rugby shoulder padding. Areas for review included personal protective equipment for sport (sPPE), sportswear garment technology, rugby; the game, padding and injury mechanisms and injury reduction methods; and auxetic structures. The subject areas involved perspectives from garment design, sports engineering and material science. Knowledge from these areas were synthesised to define the gaps in research.

The literature review was designed to critically review the current standard of sPPE materials and apparel for impact and collision sports as well as current assessment methods. The review had a sport specific focus on rugby as sPPE is designed to reduce injury risks from injury patterns that are sport specific. This research focused on rugby shoulder pads; as such the review encompassed rugby shoulder injuries, the shoulder anatomy and relevant product regulations. This chapter also critically analysed current research which recommended the use of auxetic structures for sPPE generally and determined key areas for further investigation. The outcomes of the chapter informed the primary research methods required to fulfil the aims of the research.

2.1 Impact and Collision Sports

Impact and collision sports encompass injury risks from participation; the most common types of sports injuries are related to sports leading to physical contact between players (collision) and contact with an object or falling to the ground (impact), including cycling and snow sports and all-terrain vehicle sports (BCIRPU, 2013). Some sports have found higher injury risks with time; for example, rugby has seen a 36% increase in training related injuries (World Rugby, 2018). Medical advisory action to reduce the physiological load of rugby union players has been implemented as part of an eight-point plan to reduce injury rates and severity (World Rugby, 2018). The eight-point plan involved a review of the rules of the game, game analysis and injury risk assessments, aimed at improving player safety.

Moderate injury may be normalised by participants of impact or collision sport, for which impact is the nature of the game, leading to overconfidence and causing further injuries, such as in rugby union (Fie et al., 2018). Therefore, due to the nature of the game, sport injury can be caused by repeated traumas to the same body region (Kazemi et al., 2005). Injury reduction measures including rule changes and sPPE are considered to be more cost effective (Payne et al., 2016) than reactive solutions financed by health services (including the NHS in the UK) and injured participants (Bekkum et al., 2011). However, rule changes must be acceptable, adoptable and compliant with participants and coaches (Finch, 2006). As such, innovation in sPPE that encourages product uptake and player safety in impact and collision sports is a critical to injury reduction.

2.1.1 Impact and Collision Sports Injuries

Impact and collision sports can subject participants to extrinsic forces. Injury risks are associated with sporting tasks for example scrummaging in rugby, or specific injury patterns such as a wrist fracture from a fall onto an outstretched hand in snowboarding (Lee and Kim, 2011). Minor impact injuries can damage connective tissues and cause superficial injuries (cuts, bruises and lacerations). Powerful direct contact can lead to major injuries such as joint dislocation and more severely spinal and head injuries, ligament and tendon damage as well as fractures (Steffen et al., 2010). However, injuries are sport specific and each impact or collision sport has its own unique set of injury patterns and participation risks.

Sport injury severity is often defined by time out of play (Orchard et al., 2005) showing that injury reduction can influence participation. Of these sports, fewer impact injuries have been found in cricket with respective sPPE protecting against ball impacts (Newman, 2003), lessening participation risk (Orchard et al., 2005). In contrast, a study of 100 footballers reported 84% of impact injuries were to the shin (Cattermole et al., 1996) despite mandatory shin pad use (FIFA, 2014). As football is a dynamic, high intensity athletic game, football shin pads are compromised between providing impact protection without restricting player performance, a problem shared by rugby sPPE. 30% of rugby injuries have been found to occur in the shoulder region (Funk, 2012) which is frequently engaged in contact and movement during play (Helgeson and Stoneman, 2014). Rugby union participants face high injury risk, especially amongst the best players (World Rugby, 2016; Roberts et al., 2013) challenging the possibility that superior fitness, skill and experience lower injury risk. Therefore, innovation of sPPE that provides impact protection without restricting movement could reduce time out of sporting participation.

Rugby Union

Rugby union is a contact sport with defined injury patterns (Targett, 1998). Due to increased injury, World Rugby have implemented injury reduction measures through law reforms. Reforms have included clear instruction on safe and dangerous practice on the field by following correct techniques for tackling, as illustrated by the Rugby Ready handbook (World Rugby, 2014). In the case of reducing concussion risk, the exercise programme Activate (World Rugby, 2019a) was launched and has seen a reduction in whiplash by 29 – 60% when used regularly. Reduction methods have also included sPPE in the form of mouthguards, padded headguards, taping of joints, support sleeves, grease and shoulder padding. Aside from the padding embedded within the shoulder region of rugby tops, additional padding is often located at the sternum, bicep, ribs, kidney and neck, intended to protect against minor injuries like bruises, cuts and abrasions (World Rugby 2019b).

Rugby injury severity is reflected by the time taken for players to return to the pitch. There are fifteen player positions often categorised as forwards, shown in Figure 1 as positions 1 – 8 and backs, positions 9 – 15, with no significant differences in injury severity (Brooks and Kemp, 2011). Individually however, injuries to the upper and lower extremities that led to significant time out of play affected similar playing positions. For example, neck injuries that led to over 150 days of absence due to impact or collision were reported more frequently for Loose-head prop's (tackling 57% and scrummaging 29%), Open-side flanker's (tackling 63%), Hooker's (tackling 38%, general collisions 25% and scrummaging 19%) and Centre positions (tackling 44%)(Brooks and Kemp, 2011). Other impact injuries to the upper extremity that led to over 150 days of absence included the head, for which both Centres were at highest risk (tackling 44%). Brooks and Kemp (2011) demonstrated that positions encompass specific injury risks and yet previous research has not investigated whether specific playing positions are more likely to wear sPPE.

Figure 1: Rugby Union playing positions (BBC, 2019)

Rugby union consists of two forty-minute halves not including breaks for injury and as such the elapsed time tends to be greater than eighty minutes. Rugby has the highest risk per player per hour (Moore et al., 2015) of all the major sports. On average rugby players sustain around 46 - 62 injuries per 1,000 hours of match play (Yeomans et al., 2018; Swain et al., 2016). Swain et al., (2016) found that 36% of injuries were moderate to severe, which led to more than one week of time lost from play for participants. Only at a professional level are match and team doctors required to be present by the laws of the game (World Rugby, 2019a). Research has identified that new injuries accounted for 82% of rugby injuries whilst 18% were recurrent, with severity higher for the latter (Brooks et al., 2005). Therefore, increased severity for recurrent injuries demonstrates that participants return to play before making a full recovery from treatment, indicating that injury reduction methods should be improved.

Rugby Shoulder Injuries

Shoulder impact injury risk is higher for Loose-head prop (scrummaging 66%), Hooker (tackling 57%) and Centre positions (tackling 68%)(Brooks and Kemp, 2011). In general, rugby participation can lead to fractures, sprains and dislocation, which result from direct blows to the top of the shoulder (Harris and Spears 2010), as shown in Figure 2. Scrum induced injury patterns include tearing of the pectoralis major muscle (Beer and Bhatia 2009). This muscle injury is most likely to occur when a forward player has their arm engaged with another player in a scrum, with the upper arm in abduction and the forearm around the adjacent player. When the scrum collapses, the contracting muscle tears off the tendon at its insertion. Minor shoulder injuries can also include soft tissue damage and lacerations; these have potential to cause distraction during play which could lead to major injuries (Harris and Spears, 2010) affecting quality of life, and therefore should not be overlooked.

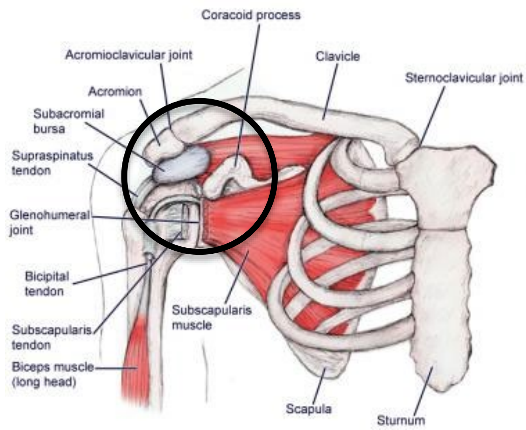


Figure 2: Shoulder anatomy muscle, anterior view, circled is the top of the shoulder (Kishner, 2015)

The range of shoulder mechanisms required to perform the identified tasks in rugby include abduction, adduction, rotation, circumduction and flexion in a multitude of directions. As such the shoulder's many dynamic movements are required but injury can also result from contact and collision related impacts. The region is engaged in contact with another body during the shoulder tackle – front on, shoulder tackle – side on smother tackle, tackle from behind, the ruck, the maul and scrums (World Rugby, 2014), as shown in Figure 3. The highest number of shoulder injuries in rugby have been recorded for tackles (Swain et al., 2016). The highest number of tackles per match have been recorded for Blind Side and Open Side Flankers, 2nd Row and Number 8 positions (Schoeman et al., 2015); therefore research suggests that these positions are at greatest risk of shoulder injury.

Figure 3: Rugby movements involving shoulder contact (World Rugby, 2014) including shoulder tackle a) front-on and b) side-on, c) smother tackle, d) tackle from behind, e) ruck, f) maul and g) scrum

The frequency and severity of shoulder injuries to rugby players has increased (Beer and Bhatia, 2009). The majority of rugby shoulder injuries occur from a fall (Figure 4) or tackle, resulting in varying levels of severity (Funk, 2012). The less severe rugby injuries from direct blows result in soft tissue bruising of the trapezius, the deltoid, the pectoralis major muscles and those surrounding the shoulder (Beer and Bhatia, 2009). More severe injuries occur by direct falls onto the shoulder which can cause swelling and dislocation of the sternoclavicular joint, spraining or tearing of the rotator cuff. Spraining or dislocation of the acromioclavicular (AC) joint typically occurs when the posterosuperior of the shoulder strikes the ground (Beer and Bhatia, 2009). Therefore, despite the requirement for dynamic shoulder movements throughout rugby, participation involves multiple impact and collision shoulder injury patterns.

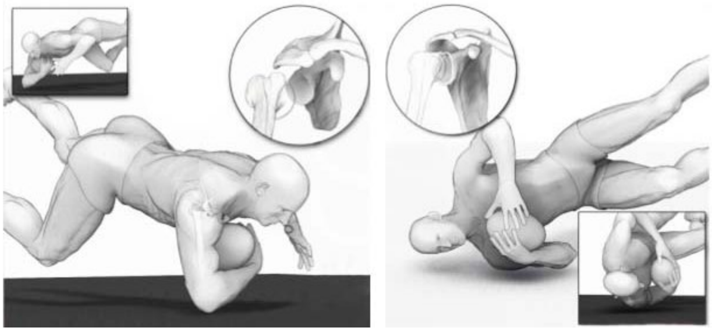


Figure 4: Rugby tackler injury (Funk, 2012)

2.2 Personal Protective Equipment for Sportswear (sPPE)

sPPE is designed to transfer impact energies into tolerable forces for the body (Gould et al., 2019). The mechanisms of protection against impact include energy dissipation and absorption as well as reduction of penetration, lacerations and abrasion (World Health Organization, 2010; Yeh et al., 2016). The type of sPPE and the selected protection mechanisms are dependent on the body region, injury patterns, forces, the tasks of the sporting role as well as the athletic and dynamic movements involved (Watkins and Dunne, 2015). Many sPPE solutions have been devised including leather (Figure 5a), various combinations of rubber (Figure 5b), compressed foam, industrial foam rubber as cushioning layers and a stiffer material or dilatant material (Figure 5c) in some cases as a shell aimed to spread the impact force energy and reduce pressure (World Health Organization, 2010; Yeh et al., 2016).

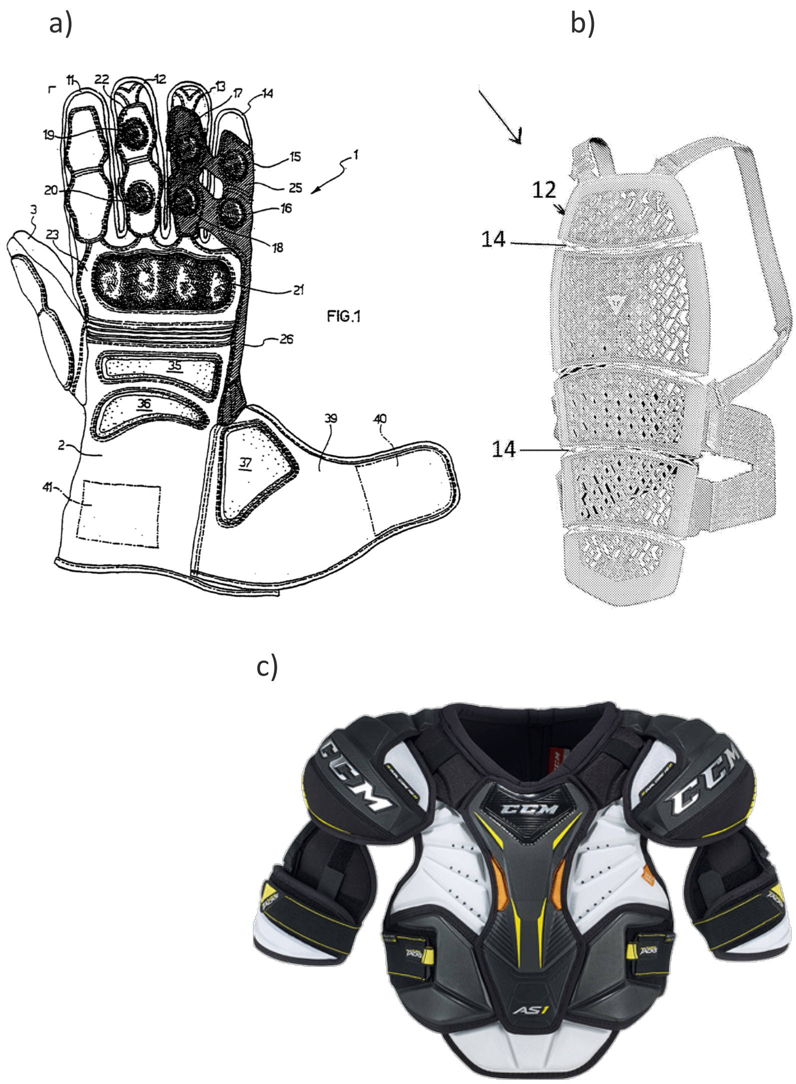


Figure 5: Examples of sPPE including a) leather embedded within a motorcycling glove (Mazzarolo, 2002), b) rubber back protector (Boria, 2016), c) dilatant material embedded within upper body protection for hockey (D30, 2020a)

2.2.1 Properties of Impact Protective Materials

There are different processes of product testing to ensure that the sPPE materials are fit for purpose (World Rugby, 2019b; ASTM, 2004). Applications of force have been categorised as tension, shear, compression and impact (ASTM, 2017). High tensile strength is critical for sportswear which are subject to extension and stretch through wear and body movement and assessed through tensile tests (ASTM, 2019). Whereas, unaligned forces known as shearing; high shear strength shows an ability to resist a structure from sliding against itself in opposing directions, highly desired for resistance to impact forces (Yang et al., 2015). Compressive strength is the maximum load at failure divided by its cross-sectional area (Guo et al., 2017) and through impact tests a material's protective capability can be examined (Mattei et al., 2012). Product testing is dependent on the type of impact that the body is subject to, including dissipation, deceleration, deformation and absorption (Watkins and Dunne, 2014). However, regulations for sPPE including rugby shoulder padding (World Rugby, 2019b) focus particularly on impact tests, often neglecting subjective assessments such as comfort and mobility.

Most impact protective materials combine energy transformation mechanisms (Watkins and Dunne, 2015). In the absorption of impact energy, elastic energy is stored in protective materials, enabling rebound of the strike from its location of impact (Laing and Carr, 2015). Where energy cannot rebound from an impact protective material, a deceleration mechanism reduces the force to a value considered safe for the body. Protective materials that include a rigid outer shell enable gross deformation and load spreading, therefore decreasing the pressure on the protective pad. However, a rigid outer shell is not ideally suited to padding likely to come into contact with a participant's face for example and is not permitted in the World Rugby Body Padding Specification (2019b); as such there are limits to the level of protection sPPE is able to provide product users.

2.2.2 Commercial Protective Materials for sPPE

Ethylene vinyl acetate (EVA) foam (Figure 6) is a widely used protective material for sportswear including rugby (Arensdorf and Tobergte, 2005). EVA is a closed-cell foam, that is soft and considered to have good shape recovery after deformation (Zujiang et al., 2014). The raw materials required to fabricate EVA foam are fossil fuels, a non-renewable source (Higg Material Sustainability Index, 2018). In addition, closed cell foams offer poor conformability (Griffiths, 2009) to the curvatures of a moving body, they are unable to extend (Borreguero et al., 2012) with the stretch of the sportswear fabrics that they are joined to.

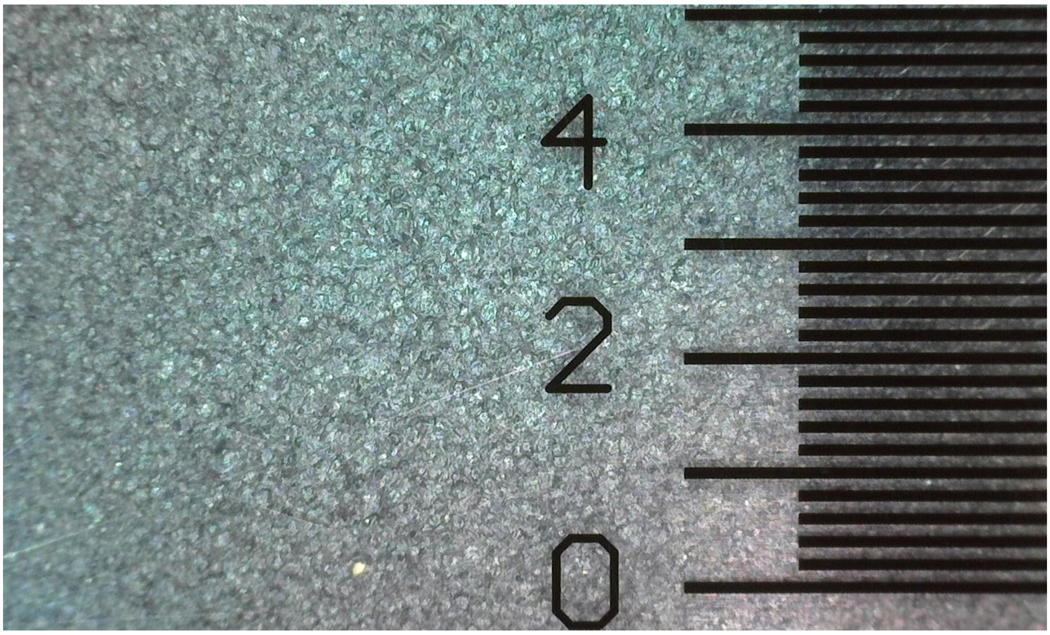


Figure 6: Cross-section of EVA foam viewed under a Dino-Lite Pro micrograph at Manchester Metropolitan University, image includes an accurate 5 mm scale (Authors Own Image, 2017)

Open cell foams (Figure 7) are more easily compressed under impact as they have a porous structure making them less suited to impact protection than closed-cell foams (Landauer et al., 2019). However, open cell foams can provide enhanced impact protection by adapting density, cell wall thickness, thickness of the overall structure and the proportion of material to gas (Watkins and Dunne, 2015). The benefit of an-open cell foam in contrast to closed cell foams is the potential for breathability and flexibility, compressing and expanding as needed during body movement (Watkins and Dunne, 2015). Open cell foams are frequently employed as the cushioning mechanism in impact protective devices due to the porous structure (Wyner et al., 2017). For example, open cell foam has been used to line helmets (Talluri, 2006).

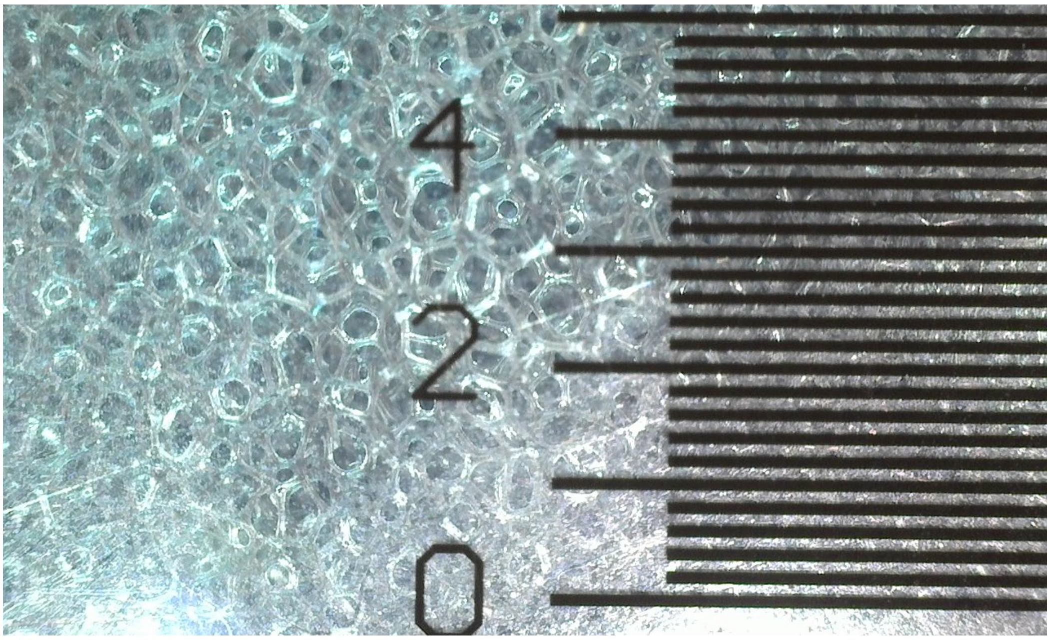


Figure 7: Cross-section of open-cell foam viewed under a Dino-Lite Pro micrograph at Manchester Metropolitan University, image includes an accurate 5 mm scale (Authors Own Image, 2017)

Dilitant Materials

Dilatant materials have a free-flowing molecular structure, locking under impact to reduce peak forces. A dilatant material (Ferguson, 2007) absorbs and dissipates impact energy and after which its molecules return to a free-flowing state (Figure 8) such that the material becomes flexible (Dura et al, 2002). Different levels of protection are provided at low to high speed impacts, as the dilatant material reacts to its impact environment enabling a high level of energy absorption (Dura et al, 2002) as well as breathability (Chin and Wetzel, 2008) and conformability (Balslev, 2006). These characteristics are thought to enable dilatant materials to provide a greater compromise between protection and fit compared with closed and open cell foams. Dilatant materials have been used for hockey, motorcycling, American football and ice hockey (D30, 2020) but they do not offer the softness or cushioning effect of open or closed cell foam, limiting some sPPE applications.

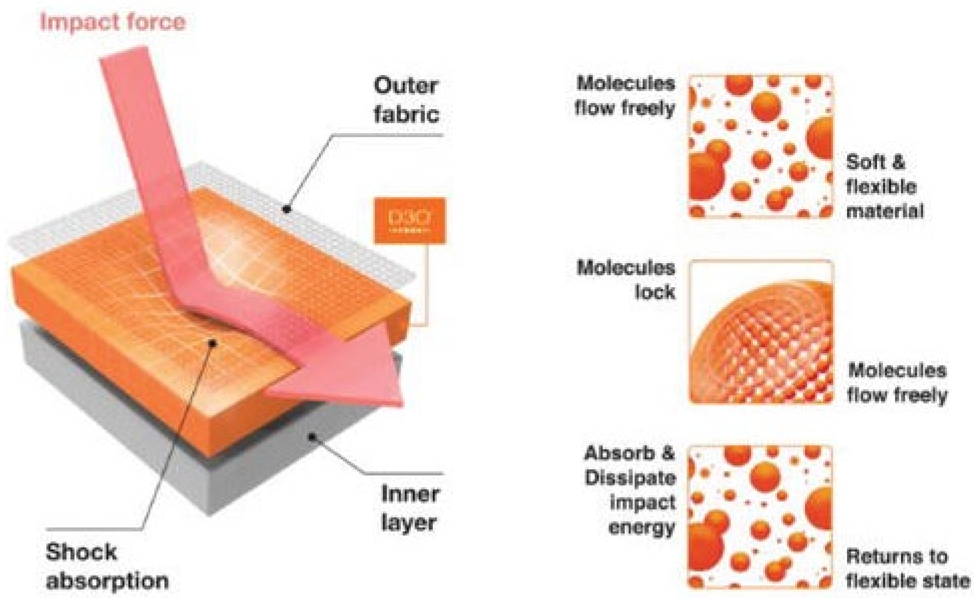


Figure 8: Schematic of a dilatant material with free flowing molecules which lock under impact (D30, 2020b)

2.2.3 Regulations for sPPE

Padding is typically subject to an impact test related to the standards of a specific sporting body (ECS, 2003; ECS, 2003b). Rugby shoulder padding must adhere to the World Rugby Body Padding Specification (2019b), in which a 5 kg flat face drop mass with an impacting energy of 14.7 J strikes the PPE rested on a steel anvil (Figure 9). To pass the test, peak acceleration must exceed 150 g meaning that World Rugby limit the amount of protection offered by shoulder padding. The performance of sportswear and respective fabrics is typically assessed with specific test methods, often product or sport specific. This is because different sports encompass unique environmental (climate, indoor/outdoor and on land/in water) and physiological (impacts/collisions, dynamic movements and tasks) demands (Uttam, 2013) and therefore the respective garments have different functional requirements.

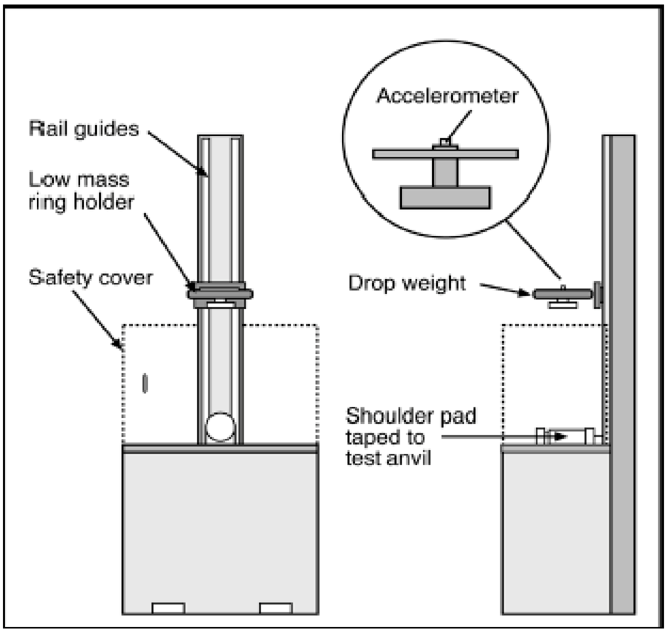


Figure 9: Apparatus for impact testing shoulder pads (World Rugby, 2019b)

World Rugby (2019b) provisions relating to rugby players dress state that padded materials must comprise of soft and thin materials. The rugby shoulder pads are to cover the shoulder and collarbone only and may have a density of no more than 45 kg/m^3 nor be thicker than 1 cm when uncompressed. The permissible padded area of coverage is shown in Figure 10. Padding use is optional, meaning that the World Rugby Body Padding Specification (2019b) does not specify a minimum area of coverage. Padding no thicker than 0.5 cm uncompressed is permitted outside of the zone of coverage and is not subject to impact requirements (World Rugby, 2019b). Pads covering the entire permissible area offer the greater possible protective coverage, but they may decrease the wearers mobility (Barbour, 2014).

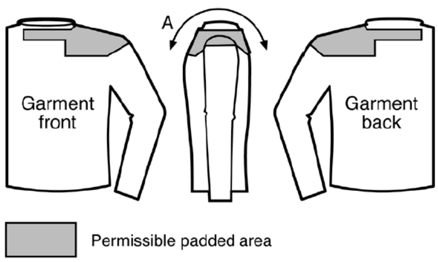


Figure 10: Shoulder padding zone of coverage (World Rugby, 2019b)

Tests such as fabric bulk density offer insight into the comfort and mobility provided by padding. Bulk density is associated with the mass and thickness of the padded material (Hur et al., 2013), user experience of bulkiness is dependent on factors including climate, body part and movements associated with that sport and the respective sPPE. Additionally, there are standards for evaluating the comfort, fit and function of protective clothing in active positions (ASTM, 2018). Active positions are selected from a range of motions associated with the role for which protection is required (Dabolina et al., 2019). The protective clothing standard ASTM (2018) F-1154 is comprised of eight active positions including raising arms above the body (Braganca et al., 2016). However, this test method is not currently included in the World Rugby (2019b) Body Padding Specification for shoulder padding despite stipulating that pads must not cause discomfort or restrict normal playing movements.

2.2.4 sPPE Construction Methods

There are many construction methods for sports apparel, as the invention of new ones has given rise to a plethora of machines for seaming and embedding. However, most sports garments are still produced by cut and sewn methods (Troynikov and Watson, 2015). The suitability of embedding and joining construction methods depend on the fabrics and materials selected for that garment application. When making sPPE, lightweight stretch fabrics are combined with non-stretch pads (Figure 11a), which can restrict user movements (Tsui, 2011). Figure 11b shows that both a straight lock-stitch and twin needle coverstitch are used to embed padding; only the former prevents the stitched region of fabric from stretching due to firmly linking together two threads (McLoughlin and Hayes, 2015).

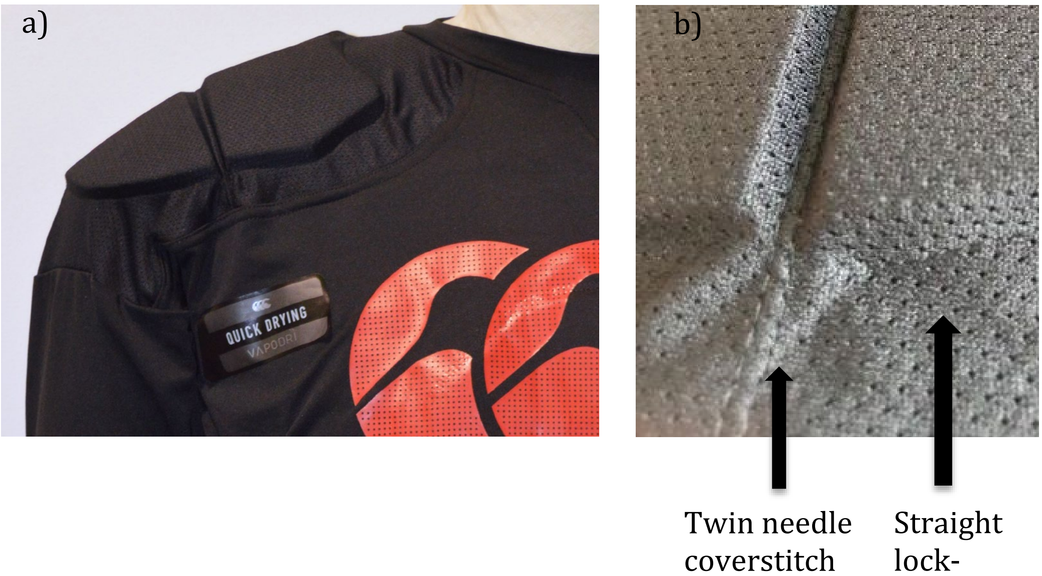


Figure 11: a) Rugby shoulder padding fitted to a mannequin b) Close-up of the padding embedding method (Authors Own Image, 2017)

Venkatraman and Tyler (2016) note that flat lock (coverstitch) seams are used to provide enhanced comfort. Use of the flat locked seam to join padding to a rugby top can be seen in Figure 12a. The benefit of flat locked stitches in sportswear is that they reduce bulk (McLoughlin and Hayes, 2015) and have a spring-like quality allowing great extensibility and recovery along the length of the seam (Hayes, 2018). Padding can be embedded within a pocketed region of a garment with overlocked seams (Figure 12b). However, this method creates added bulk at the seam as it is not sealed flat against the garment, so is considered less desirable compared to flat locked seams shown in Figure 12a.

a) b)

Figure 12: a) Shoulder padding joined to a stretch sports top with a flat lock/coverstitch seam, b) PPE embedded within a pocket joined to the top with overlock stitch (Authors Own Image, 2017)

Within the sportswear industry, garment technology that produces a seamless appearance has become increasingly desirable. Heat sealing and laser methods have been utilised for thermoplastic materials and methods include hot air (Zimmer et al., 2018), hot wedge (Timothy and Hupp, 2013) and ultrasonic welding (Szafranska and Korycki, 2020). Integrally knitted garments, which are essentially knitted in one piece with few or no seams at all have become a promising construction method for functional performance sports garments (Troynikov and Watson, 2015). Vacuum moulding (Figure 12a; Figure 13) and 3D printing PPE (Brennan-Craddock et al., 2012; Cazon-Martin et al., 2018) has also encouraged this appearance. The benefit of these methods is the reduction of added bulk at seam edges because padding bulk can cause sPPE to be uncomfortable (Park et al., 2014).

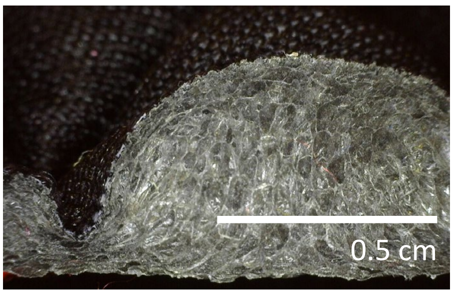


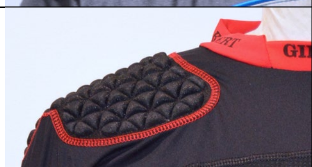
Figure 13: A micrograph cross-section of segmented closed cell foam (manual measurements indicate scale based on 0.5 cm depth of segments) vacuum moulded to stretch fabric for sPPE (Authors Own Image, 2017)

Since protective materials are usually made of non-stretch componentry, other methods must be used to offer mobility. One method of helping pads to conform better to the body is to simply segment protective materials so that they can bend more easily (Watkins and Dunne, 2015; Figure 12a, Figure 13). Even rigid or non-stretch padding may be manipulated to conform to the body more effectively using segmenting techniques. Segmenting can be comprised of individual inserts of padding within channels of the overall pad by stitching (Diamond, 2012) or a process of shaping and laminating foams to stretch fabrics through vacuum moulding (Staub et al., 2017). Segmentation methods also include scoring part way or fully through padding (Morrow and Winningham, 2006) with a blade, laser-cutting or die-cutting. However, sPPE design involves compromises because slicing or cutting away padding consequently affects protective coverage.

2.2.5 Commercial Rugby Shoulder Padding

Table 1 shows World Rugby (2019b) approved shoulder pads differ by segmentation type and coverage. Segmentation types include vacuum moulding and cut-segmenting in triangular, honeycomb and rectangular repeated segments. Pad shape and coverage differ between tops, in particular shaping to the contours of the collarbone, neck and shoulder were identified as a technique used to improve the conformability of the padding. During practise and match use, conformability of these pads to shoulder movement and garment stretch encourages use as discomfort is a leading factor in product uptake (Hughes et al., 2020). Closed-cell foam was the only padding within the tops and flat lock/coverstitch seams were the most frequently used construction/embedding method for the tops comprised of stretch fabric composed of nylon and elastane (compositions shown in Table 1). Where pads featured segmentation and reduced/shaped padding coverage, it is likely that it would affect protective coverage compared to non-segmented pads, for which padding has not been cut or scored away in place of improved fit.

Table 1: Rugby shoulder padding market research

PPE	Indicative price (£)	Composition (identified from care labels)	Image of shoulder region of rugby shoulder pads	Embed/ Joining Methods	Coverage	Elements aiding comfort and conformability
A. Canterbury Vapodri Raze	35	84% Polyster 16% Lycra Pad: 100% EVA foam, Breathable mesh cover *		Embedded: S/S at pad outer edge and T/N C/S between pads	Medium	Non-segmented foam: 4 foam pads separately embedded Shaping: neckline
B. Canterbury Vapodri Raze Pro	53	84% Polyster 16% Lycra Pad: 100% EVA foam, Breathable mesh cover*		Embedded: T/N C/S	Full shoulder to collar bone	Cut-segmented: honeycomb pattern Shaping: neckline and collarbone
C. Gilbert Triflex Match V3	80	Polyster* and lycra* mix Pad: 100% EVA foam		Joined: S/S	Full shoulder to collar bone	Vacuum moulded: triangular pattern Shaping: neckline and collarbone
D. Gilbert Chieftain V3	75	Polyster* and lycra* mix Pad: 100% EVA foam		Embedded: C/S	Full shoulder to collar bone	Cut-segmented: triangular pattern Shaping: neckline and collarbone
E. Gilbert Atomic Zenon	45	Polyster* and lycra* mix. Pad: 100% EVA foam		Joined to top: S/S	Medium	Vacuum moulded: honeycomb pattern Shaping: neckline and collarbone
F. Gilbert Triflex XP1	50	Polyster* and lycra* mix, Pad: 100% EVA foam		Joined: C/S	Full shoulder to collar bone drawing into a T shape	Vacuum moulded: triangular pattern Shaping: neckline and collarbone
G. Kooga IPS V	27	92% polyester, 8% elastane, 100% polyester mesh back panel Pad: Unknown moulded foam*		Joined: C/S	Medium	Vacuum moulded: triangles and rectangles forming a diamond pattern Shaping: neckline and collarbone
H. Body Armour Tech Vest BA	40	Polyster* and lycra* mix Pad: 100% Polyethylene foam		Embedded: C/S and O/L	Full shoulder to collar bone	Non-segmented: rectangular whole pad Shaping: neckline
I. Body Armour Flexitop BA	60	Polyster* and lycra* mix Pad: 100% Polyethylene foam		Joined: C/S	Full shoulder to collar bone	Cut-segmented: honeycomb pattern Shaping: neckline

*unspecified composition.
Key: T/N C/S: twin needle coverstitch. S/S: straight stitch. C/S: coverstitch. O/L: overlocked

2.2.6 Protectiveness and Comfort of sPPE

There are limitations as to how far sPPE can prevent impact and collision injury. Rugby shoulder padding is designed to attenuate forces (Harris and Spears, 2010), preventing bruising and lacerations through absorbing or dissipating impact energy from direct blows. The foams used as protection in some commercial garments are not designed to prevent more severe shoulder injuries such as dislocation. Beer and Bhatia (2009) compared peak forces of rugby shoulder padding in different thicknesses to no padding and discovered that the different pads led to a 1% to 70% reduction. However, the padding was found to “bottom out” under high impact loads (Beer and Bhatia, 2009) this effect causes the material to flatten, offering little protection when the athlete was most vulnerable.

The performance of sPPE is measured in relation to the product’s ability to protect against respective injuries, utilising quantitative test methods usually in relation to specific sporting bodies. Padding should gradually decelerate an impacting body and spread the impact force into a form of energy less harmful to the body (Watkins and Dunne, 2015). In order to maintain certain sportswear properties such as good stretch, a light-weight sensation and conformability as well as injury reduction some materials have a limited protective function (Watkins and Dunne, 2015). Therefore, pad designers are challenged in producing sPPE with a protective functionality that does not restrict wearer movement.

Stretch is important in sportswear because simple body movements may extend the body’s skin by about 50% (Senthilkumar et al., 2012a). In turn, fabric should respond by stretching with the body’s extension and recovering upon relaxation. Elastic garments are required to improve the stamina and speed of an athlete through quick recovery and lower stress with higher elongation (Senthilkumar et al., 2012b) enhancing the stamina, speed and power of the sports person. Uncomfortable sPPE could lead to irritation which may interfere with an individual’s ability to concentrate on a task. Therefore, one of the major challenges of designing sPPE with non-stretch pads is the difference between skin extension during movement and restrictiveness of the pads.

Where padding resists the expansion of the stretch garment, pressure can be higher, affecting the comfort of the wearer (Jin et al., 2008). Garment pressure is generated when the girth of a garment at a particular body region is smaller than that of the body at the corresponding region (Wong et al., 2004) and can be measured by a pressure measurement device (Senthilkumar et al., 2012a). Pressure is affected by factors that include the shape of a body part - which may change under movement, such as the shoulder or knee, type of fabric used and finally the fit of the garment, influenced by its design. Pressure comfort is not included in the World Rugby (2019b) Body Padding Specification for shoulder padding, but locating regions of padding that generate higher pressure could describe the effect of padding fit issues on wearer comfort.

Product performance assessments of sPPE focus on the effectiveness of product function (Sun et al., 2012) such as impact force attenuation (Harris and Spears, 2010). However, perceived perceptions of sPPE can describe how effectively users feel they are able to work and play and have been conducted for sports including inline skating, skateboarding and snowboarding (Kroncke et al., 2008) and football (Braham et al., 2004). Bulkiness has been reported for sPPE as a cause for restricting user movements, identified in terms of the padding weight (Tsui, 2011). A comfort model by Webster and Roberts (2009) identified that the PPE user also perceives weight as an element of comfort. Therefore, perceived weight comfort could be used to describe sensations of padding bulkiness.

In contrast to product performance, product comfort is predominantly investigated through qualitative research methods including focus groups and interviews (Roberts et al., 2001; Webster and Roberts, 2009). The comfort model developed by Webster and Roberts (2009) was segmented into six dimensions of perceived weight, thermal comfort, aesthetics and sensorial comfort and with protection second to fit as the most important factor in the user experience of comfort. A survey of 15-year-old schoolboy rugby union players by Finch et al., (2001) confirmed that the main reason for not wearing headgear was discomfort (61%). The study also identified that a belief in protective capabilities influenced more confident and risk-taking playing behaviour. Researchers, Branson and Sweeney (1990) acknowledge that the sPPE product user perceives its comfort. Therefore, protection can be perceived by the wearer as a realm of comfort and in addition to mechanical assessments can be assessed through user perceptions.

2.2.7 User-Centred Design Approach to sPPE

The design of sPPE involves achieving a balance between the level of protection that can be provided with other factors like mobility and comfort. Watkins and Dunne (2015) presented a design strategy for the development of functional clothing. The three-stage sequential process has transferability to rugby shoulder padding as it begins by firstly determining the problem, secondly ideating solutions and finally, implementation of the solution and assessment of its effectiveness. This formula is applied for other functional clothing design strategies (McCann and Bryson, 2014) as well as PPE for healthcare (Larson and Liverman, 2011). Strategies for sPPE and more specifically rugby shoulder pads have not been established but it is possible to tailor each stage to have relevance to rugby shoulder padding.

Stage 1: Determining the sPPE Garment Design Problem

The first stage of a user-centred design process for functional clothing defines the problem, via the user, activity, body region and function (Larson and Liverman, 2011; McCann and Bryson, 2014; Watkins and Dunne, 2015). Even though protection is the function of sPPE garments, the design problem is defined by all factors which may influence product use. This requires an investigation into product function and its present standard, regulations from the respective sporting body, the nature of the sport as well as user perceptions, injury patterns and respective body movements. Secondary research into user and product analysis may provide knowledge for this stage but in the case of rugby shoulder padding, research into subjective factors involving user comfort is limited. As such, user-centred design of sPPE garments may require investigation of the problem by examining perceptions of product use and commercial product analysis (Watkins and Dunne, 2015).

Stage 2: Design Ideation and Development of sPPE

Development of a design solution comes after synthesising findings regarding the user, sport, body region and product into the design problem. These findings direct the designer to the respective commercial realities, function (demands of the activity) and form (product), known as the Design Tree Model (McCann and Bryson, 2014). This enables the development of a hierarchy of design criteria, in the case of sPPE for example impact protection is thought to outweigh mobility in importance (Ledbury, 2018) as it is the function. The problem with this hierarchy is that discomfort has been identified as a reason for not wearing sPPE during rugby participation (Finch et al., 2001). Therefore, the ideation phase of sPPE development requires an emphasis on the enhancement of user-comfort which can be evaluated through participant interviews (Watkins and Dunne, 2015) and wearer trials (Cooper et al., 2017). During this second stage of functional design, tasks include prototyping, evaluation, revisiting and refining solutions to the design problem (Hunter, 2016).

Stage 3: Implementation and Assessment of sPPE Effectiveness

The final phase of functional clothing design requires field use (implementation) and evaluation within the real-world scenario (Larson and Liverman, 2011; Watkins and Dunne, 2015). This phase is required to determine the performance standard as well as unknown consequences of use (Larson and Liverman, 2011). Unidentified consequences of wearing rugby shoulder padding may relate to any of the scenarios involved during use which may not be possible to determine without participation in rugby. There is limited research into the effect of rugby shoulder padding design on user comfort and perceptions, which can provide confirmation as to whether the design problem has met a solution (Classen, 2018).

User Centred Design Approach to Rugby Shoulder Padding

Developing strategies for the enhanced conformability of rugby shoulder pads has potential to improve product uptake. At present World Rugby (2019) stipulations for padding standards focus on performance. In contrast, user centred design approaches determine users physiological and psychological needs before ideating and developing product solutions (Suh et al., 2010). Findings for how to improve padding conformability could be mapped out over a user-centred design strategy in order to improve wearer comfort. The strategy would enable pad designers to gage user experience alongside performance assessments at each development stage ensuring user satisfaction.

Rugby shoulder pad discomfort has been reported (Hughes et al., 2020; Finch et al., 2001) and fit issues have been commented on for specific pad characteristics (Venkatraman and Tyler, 2016) yet there is limited research into the effect on comfort. Garment technology including overall fit and pad positioning have also been neglected from assessments of padding comfort. However, this research focuses on the enhanced conformability of rugby shoulder padding rather than the overall garment. Investigating one pad characteristic, such as segmentation, through quantitative research methods would benefit from objective and accurate results (Fink, 2015) which could be mapped out against a user-centred design strategy to improve the implementation of these materials.

2.3 Auxetic Structures in Sports Apparel

Auxetic materials are amongst the most promising new material applications for sPPE, due to their ability to offer enhanced impact force limitation (Lisiecki et al., 2013; Allen et al., 2015) and indentation resistance (Alderson et al., 1994; Chan and Evans, 1998), biaxial expansion (Martin, 2011; Cross et al., 2015), synclastic curvature (Lakes, 1987; Wang and Hu, 2014) and breathability (Sanami et al., 2014b). The negative Poisson's ratio (NPR) of auxetic structures can be described in terms of geometric frameworks at the macro, micro or nanostructure and the respective deformation mechanisms to external loadings (Ashby et al., 1995). The mechanical properties of auxetic structures relate to their geometry (Figure 14; Ashby et al., 1995) and therefore, can be associated with different applications; these shapes include arrowhead geometries (Figure 14a) re-entrant geometries (Figure 14b), chiral (Figure 14c) and rotating units (Figure 14d). NPR arises due to the unit cell opening and closing mechanism under respective tension and compression (Sanami et al., 2014a).

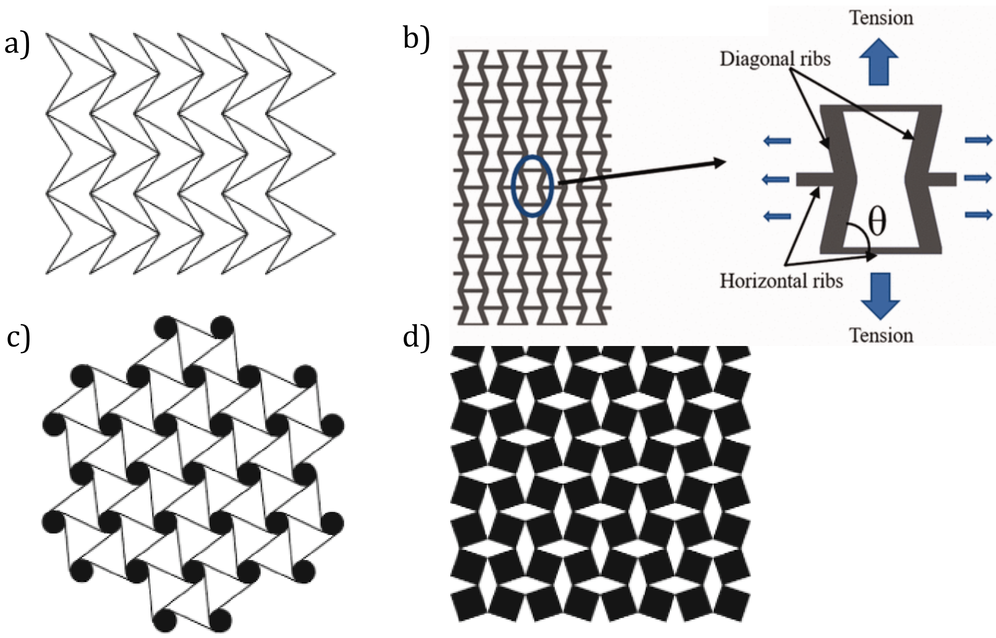


Figure 14: Auxetic structures including a) arrow-head (Lim, 2014), b) re-entrant with close up of one unit cell and eight ribs (Zhao et al., 2019), c) chiral and d) rotating square units (Lim, 2014)

Auxetic structures have been fabricated for functional clothing. Commercial fabrication methods have included moulding PPE for an American football top (D30, 2015), printed PU auxetic shapes for trainer exteriors (Toronjo, 2013), applied in-plane. Developments of in-plane auxetic structures have been produced through additive manufacture (Jiang, 2016) as well as textiles, yarns and fabrics (Hu et al., 2011; Sloan et al., 2011; Wright et al., 2012; Bhattacharya et al., 2014; Lim, 2014), although not yet used commercially. Fabrication methods for through-the-thickness NPR including open cell foam conversion (Allen et al., 2015), steam-penetration of closed cell foams (Fan et al., 2018) also require further development for commercial use in sPPE. Auxetic structures have also been laser-cut to segment sheets (Mizzi et al., 2020) and cut-segmentation is commercially used for rugby shoulder padding and therefore is an effective route to producing auxetic sPPE commercially.

The theoretical Poisson's ratio (v) range for isotropic auxetic materials is $-1 < v < \frac{1}{2}$ (Mott and Roland, 2012). Isotropic structures have the same Poisson's ratio in all directions, unlike anisotropic structures where Poisson's ratio can change with direction (Evans et al., 1994). Altering the Poisson's ratio will change the structure's indentation resistance; shear modulus and toughness (Evans et al., 1994). Therefore, the ability for an auxetic material to limit impact forces is dependent on particular elastic constants, which include its Young's, shear and bulk modulus. A particular characteristic of auxetic materials is that the shear modulus is high while the bulk modulus is low (Evans, 1991a), enabling improved indentation resistance (Lakes, 1987) which is preferable for sPPE.

It is possible to determine the stress and deflection properties of a material from ascertaining its Poisson's ratio. When a structure is stretched, resulting in dimensional changes, Poisson's ratio can be calculated as the ratio of that change (Figure 15). Poisson's ratio is the diameter of the test specimen before and after elongation, divided by the length of the specimen before and after elongation (Rosato and Rosato, 2003). A method of measuring Poisson's ratio is by combining a tensile test with digital image correlation (Fila et al., 2018). If the material is not isotropic, then its Poisson's ratio will have more than one value (Rosato and Rosato, 2003), to potentially exploit the benefits associated with both auxetic and conventional materials.

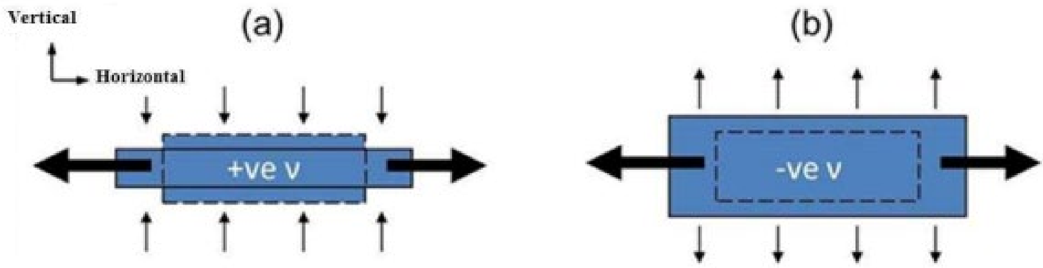


Figure 15: Lateral (vertical) deformation due to Poisson's ratio under tensile axial (horizontal) loading for a) conventional material and b) auxetic material. Thick and thin arrows correspond to deformation due to loading and Poisson's ratio, respectively (Duncan et al., 2018a)

2.3.1 Auxetic Structures

A wide variety of auxetic structures have been designed and are presented in this section. The finite element method is a route to obtaining and comparing the properties of auxetic shapes and structures for different uses (Lee et al., 1996; Scarpa et al., 2000; Huang et al., 2002; Yang et al., 2003). Adjustments in the geometry of auxetic structures have altered NPR values, and therefore offer a route to manipulating the mechanical properties (Wu et al., 2018). This section reviews established auxetic structures with the potential to offer protection for sPPE.

An auxetic re-entrant honeycomb unit cell is comprised of ribs that are bent and protrude inward (Yang, 2004)(Figure 16). Negative Poisson's ratio re-entrant structures can be made from honeycombs by mechanically inverting each cell, provided that the cell walls are sufficiently flexible (Lakes, 1993). Research of auxetic honeycomb shapes largely focus on influencing factors such as geometric effects (Yang et al., 2003; Figure 16), density variations (Whitty et al., 2002) material constants (Huang et al., 2002) as well as electromagnetic, mechanical (Smith et al., 2002) and damping properties (Scarpa et al., 2000; Yang et al., 2004). Elipe and Lantada (2012) identified that the re-entrant structure had the most negative Poisson's ratio in their research. Additionally, the ability to induce NPR in conventional structures with honeycomb cells such as foam offered greater potential for its use including sPPE.

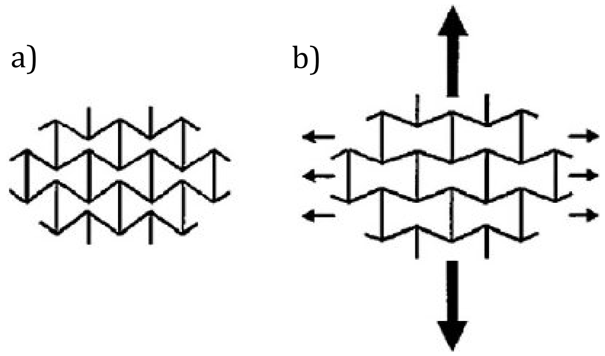


Figure 16: Re-entrant honeycomb structure showing a) its geometry and b) arrows show the geometry under lateral expansion (Carneiro et al., 2013)

Grima and Evans (2000) gave the earliest account on the NPR and associated effects of rotating connected squares (Figure 17) exhibiting a negative Poisson's ratio of -1. They showed that stretching the space filling tessellation of the structures resulted in relative rotation of the rectangles. The pore opening nature of the structure is considered useful for pore size variability applications (Gatt et al., 2015) such as smart filters and related systems. However, the structure was only identified as auxetic for loading in certain directions (Grima et al., 2011). Therefore, the pore opening properties of the structure were more consistent than properties relating to shock absorbency.

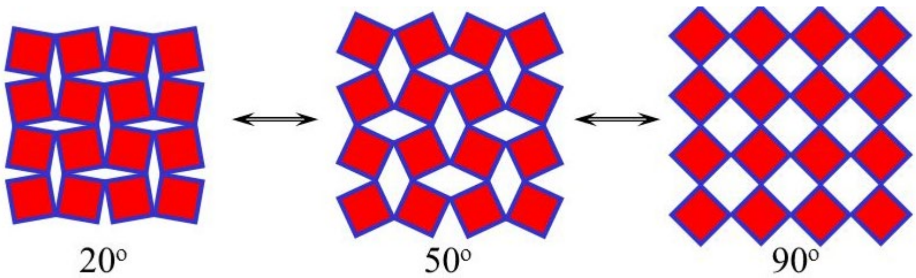


Figure 17: Rotating squares opening mechanism (Grima and Evans, 2000)

Grima and Evans (2006) expanded their work on rotating auxetic shapes to include triangles. The rotating triangle structure benefited from a wide range of Poisson's ratio values; the shape of the triangles and the angles between them were relative to the magnitude and sign of their Poisson's ratio (Lim, 2015). Grima et al., (2012) indicated that the structure was useful for explaining the behaviour of auxetic foam surface density, through which the triangles represented a two dimensional projection of the joints in NPR foam. Alderson and Evans (2001) developed the structure into a 3D model as a rotating tetrahedral framework (Figure 18) in which the tetrahedra was rigid and free to rotate cooperatively around the tilt axis whilst maintaining network connectivity, which could be adapted and 3D printed for the development of auxetic sPPE.

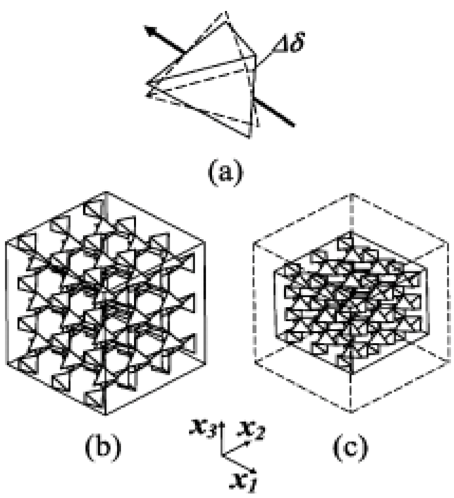


Figure 18: Diagram of tetrahedral rotation deformation mechanism, a) rotation about the tilt axis through the centre of two of tetrahedra edges, b) maximum expansion and c) maximum compression (Alderson and Evans, 2001)

In a chiral lattice model, the network is comprised of a ring connected by six ribs (Figure 19). The network allows for in-plane NPR because tensile loading in one direction causes growth through a clockwise rotation of the rings, consequently enlarging and opening out the entire network (Figure 19a; Lim, 2015). The chiral lattice is thought to have an equal shear modulus to the triangular lattice, despite its structural differences. The triangular lattice lends greater ability to expand laterally whereas the chiral lattice is subject to bending deformation (Spadoni and Ruzzene, 2012). Advanced Science News (2016) reports that chiral auxetic cellular solids offer flexible volume change, which indicates potential for enhanced protection and energy absorption in sPPE. Chiral geometry is not conventionally symmetric at the beginning so its auxetic effect can be preserved for large deformation (Kalveram, 2016), offering the benefit of varying NPR and associated effects depending on the applied load.

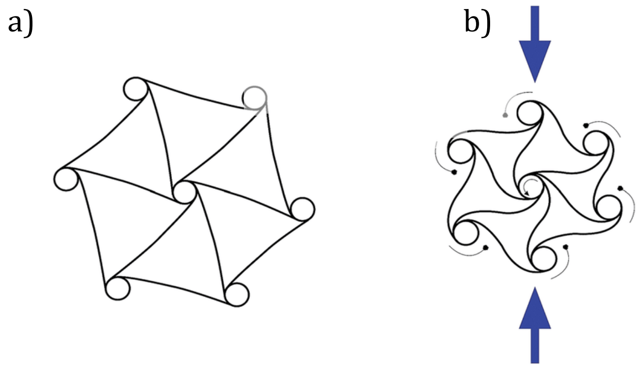


Figure 19: A chiral structure a) opened out and b) arrows show the structure under compression causing it to close (Kolken and Zadpoor, 2017)

2.3.2 Properties of Auxetic Structures

Synclastic Curvature

An advantage of auxetic structures over conventional ones is excellent shape fitting ability on a curved surface due to the formation of synclastic curvature under bending (Alderson et al., 2010; Sanami, 2014). Synclastic curvature occurs when the upper surface of the material biaxially expands and the lower surface biaxially contracts (Duncan et al., 2018a; Figure 20b). Shape fitting ability is critical to enable fabrics to be flexible in adapting to different shapes for garments or composite parts. Wang and Hu (2014) investigated the shape fitting ability of both non-auxetic and auxetic warp-knitted fabrics through placement on a spherical surface. The auxetic fabric conformed to the spherical surface (Figure 20b), whereas the conventional counterpart did not (Figure 20a). It is unknown how synclastic curvature may influence the ability to limit impact forces of an auxetic material.

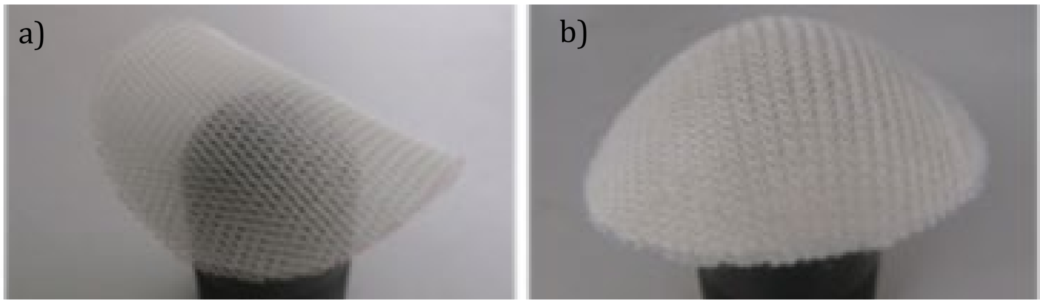


Figure 20: Shape fitting ability of spacer fabrics: a) conventional; b) auxetic (Wang and Hu, 2014)

Tailoring the density and geometry of an auxetic structure to provide synclastic curvature influences other mechanical properties. Evans (1991b) noted that properties of a material relating to buckling, shear modulus and flexural rigidity are affected by synclastic curvature. Surfaces under synclastic curvature can be stretched without distorting form due to the curvatures in opposite directions balancing each other at every point on the surface (Lewis, 2003). Tensioning the structure reduces its elasticity, decreasing its distortion when loaded. However, NPR decreases with an increase of its tensile strain (Yang et al., 2013). Therefore, despite recommendations for sPPE with auxetic elements, stretching the material with the garment during sport may have an adverse effect on its impact force attenuation.

Indentation Resistance

NPR can provide enhanced indentation resistance (Alderson et al., 1994; Chan and Evans, 1998) of 30% compared to the conventional counterparts. Enhanced indentation has been found for auxetic materials including composites (Li et al., 2020), foams (Chan and Evans, 1998), polyethylene (Alderson et al., 1994), spacer fabric (Xu et al., 2019) and woven structures (Liaqat et al., 2017). Indentation resistant is influenced by cell wall angle, thickness and density (Li et al., 2017). Indentation resistance in protective sports apparel can help prevent the skin from being penetrated by an object, which is useful in sports like football

(Ankrah and Mills, 2003; Duncan et al., 2018b) and rugby (Fuller et al., 2010) where studded shoes are worn. As well as protecting the body, indentation resistance may lead to the enhanced longevity of a material such as that used for PPE, which may be subject to repeated impacts from different objects leading to deterioration over time.

Gradient Auxetics

Gradient auxetic materials have been developed for improved bending stiffness at the transition between positive and negative Poisson's ratio regions of honeycomb structures (Hou, et al., 2014). Gradient foams have also been fabricated, by applying variable compression with rods passed through samples (Sanami et al., 2014; Duncan, et al., 2017). Gradient auxetic shapes also enabled variable compression (Alderson et al., 2013; Sanami et al., 2014). Despite no current sPPE applications, there is potential to develop auxetic structures and foams as rugby shoulder padding featuring energy absorbing auxetic regions and non-auxetic regions to diffuse and disperse the impact.

2.3.3 Applications of Auxetic Textiles

Researchers have developed various auxetic textiles, yarns and fabrics (Hu et al., 2011; Sloan et al., 2011; Wright et al., 2012; Bhattacharya et al., 2014; Lim, 2014) which benefit from in plane NPR and associated effects. Of these, Hu et al., (2011) has noted their potential applications as fabrics that change colour under uniaxial strain, blast protection clothing and medical textiles that release drugs when the pores are opened through lateral expansion. The ability to produce auxetic yarn from standard fibre and conventional textile manufacturing processes has enhanced the potential to use them commercially (Miller et al., 2009). Potential ballistics PPE applications are owed to the high tensile strength of auxetic yarns (Zhang et al., 2016), a requirement for these fabric structures. Auxetic yarns incorporated within the spandex of rugby tops could improve the strength of the fabric where it is subject to friction during impacts and collisions but are otherwise limited in shoulder padding applications.

Auxetic textiles are divided between conventional yarns knitted (Sun et al., 2019) or woven (Zulifqar and Hu, 2018) into auxetic patterns and NPR yarns (Miller et al., 2009) knitted (Goncalves et al., 2018) or woven (Ng and Hu, 2018). Sloan et al., (2011) investigated geometric properties of auxetic yarn comprised of core and wrap fibers (Figure 21). Wright et al., (2012) found that a lower wrap angle resulted in higher magnitude of NPR. For the same effect, Lim (2014) has stitched the non-core fibre in place, to control the extension of the fiber. This effect is transferable to auxetic sPPE design, it informs that the auxetic effect is controllable and demonstrates that the geometry of an auxetic structure can be influential, including the degree of its angles.

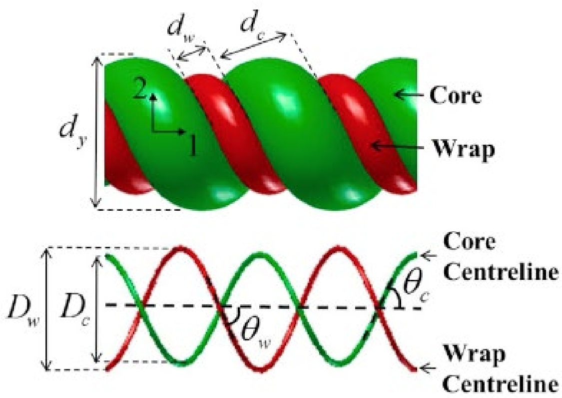


Figure 21: Diagram depicting the NPR double helic yarn and its helix angles of wrap and core components (Sibal and Rawal, 2015)

Flat knitting has enabled the fabrication of auxetic textiles. Weft knitted auxetic structures have been made using computerized flat knitting machines that are based on three kinds of geometrical structures, i.e., foldable structure, rotating rectangles and re-entrant hexagons (Hu et al., 2011). In contrast, Liu et al., (2009) reported that mesh warp knitted NPR structures have low elasticity and low recovery ability, restricting the auxetic behavior (Figure 22). The warp-knitted structures in Figure 22 and those knitted by Hu et al., (2011) show that it is possible to fabricate an array of repeated auxetic unit cells that enable lateral expansion, but are influenced by fabrication technique and structure. It has been suggested that flat knitted auxetic structures have potential in sPPE but that further research needs to be undertaken to explore their potential (Liu et al., 2010). Therefore, at present research into flat knitted auxetic structures, such as those displayed in Figure 22, have shown that fabrication methods and structural geometry are influential to auxetic behavior which may provide opportunity in the development of sPPE.

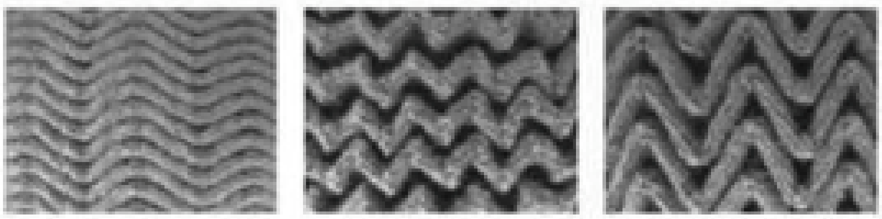


Figure 22: Auxetic fabrics with different twists (Liu et al., 2009)

2.3.4 3D Printed Auxetic Structures

Additive manufacturing is the official industry standard term (ASTM, 2012) defined as the process of joining materials to manufacture objects from 3-dimensional (3D) model data layer by layer in contrast to subtractive manufacturing methods. Jiang (2016)(Figure 23) modified 3D printed chiral structures to have softer hinges and centre cores than the rest of the structure to increase its internal rotation efficiency and magnitude of NPR. The internal rotation efficiency is controlled by the design of chiral cellular solids with centre cores and softer hinges, made possible by multi-material 3D printing. Under compression, the active ribs rotate and drive the passive ribs to rotate accordingly, leading to NPR. Therefore, using a multi-material 3D printer to manufacture auxetic structures (Huang et al., 2016) offers the opportunity to tailor the softness and hardness of the structure at designated regions to have harder cell ribs or softer corners (Jiang, 2016). However, although 3D printing can offer rapid prototyping (Schwab, 2017) it is still considered slow and high cost for mass production (Sun and Zhao, 2017) making it an undesirable manufacturing technique for sPPE.

a) b) c)

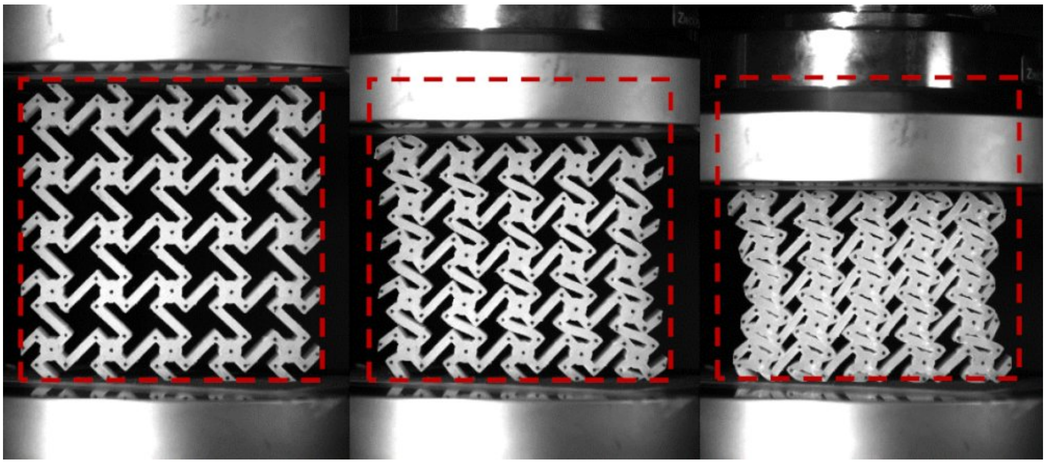


Figure 23: 3D printed chiral structure: a) uncompressed and exhibiting NPR under lateral compression b) half and c) maximum (Jiang, 2016)

2.3.5 Auxetic Foams

Under impact, conventional materials move laterally away from the axis of impact (Alderson and Alderson, 2007), causing a decrease in density at the point of impact. In contrast, when an auxetic foam is impacted, the material around the impact increases in density in both the longitudinal and transverse direction (Evans et al., 1991). Auxetic foams that are converted from open cell foam, as seen in Figure 24, offer enhanced impact and indentation resistance, versatile breathability and synclastic curvature characteristics. The traditional method of converting open cell foam to auxetic foam involves four stages in the chronological order of triaxial compression, heating, cooling and relaxation (Chan and Evans, 1997). This process causes the cell ribs to protrude inwardly, forming a re-entrant structure (Critchley et al., 2013).

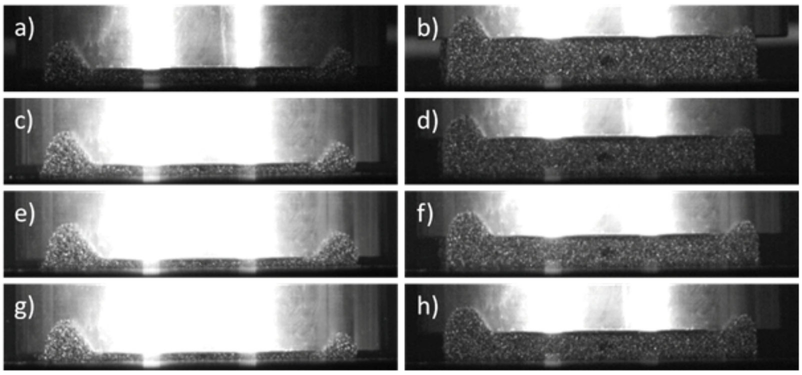


Figure 24: Images from the high-speed camera showing maximum deformation, a) conventional at 2.2 J, b) auxetic at 2.2 J, c) conventional at 3.3 J, d) auxetic at 3.3 J, e) conventional at 4.5 J, f) auxetic at 4.5 J, g) conventional at 5.6 J, h) auxetic at 5.6 J (Allen et al., 2015)

In the conversion process of auxetic foam, creasing is common leading to an inconsistent surface, particularly when producing large samples (Duncan et al., 2016). Such flaws are produced in the initial compression process of placing larger foam inside a smaller mould (Figure 25), which can be difficult to control. One tool that is used as an attempt to control the consistency of converted foam and reduce the amount of surface folding are through-the-thickness pins (Allen et al., 2017). However, typically this minimises but does not always entirely remove surface imperfections. Additionally, through-the-thickness pins mark permanent holes in foam and so developing the controlling methods for foam conversion could lead to more commercial potential for this process.

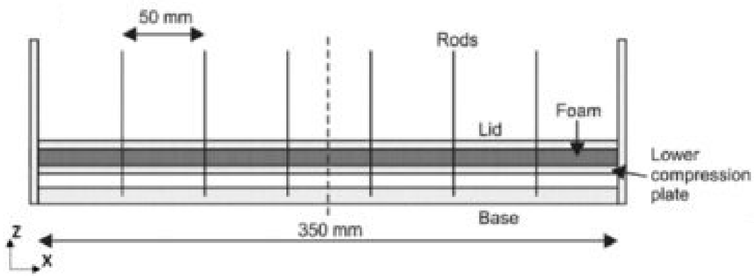


Figure 25: Cross-sectional view of closed mould with compressed foam and through-the-thickness rods (Allen et al., 2017)

Research undertaking triaxial compression to produce auxetic foam largely results in rectangular or small cylindrical sample shapes (Alderson et al., 2012). In contrast, a process of manufacturing complex shaped auxetic foam has been developed through biaxial (uniaxial) compression (Alderson et al., 2005). The process is divided by three methods of stretching, pleating, seaming separate pieces of foam as well as heating inside a curved or 'half' mould. The fabrication developments of curved and complex shaped auxetic foams highlights a potential to incorporate them into sport apparel where protective foams are shaped to fit or contour the body. However, auxetic open cell foams offer a limited solution to PPE for sports apparel as closed cell foams offer superior shock absorption.

Inducing a negative Poisson's ratio in closed cell foams has been attempted in a limited variety of trials with some success. The current thermo mechanical method of conversion typically used for open cell foams has a rupturing effect on the cell walls of closed cell foams (Choi and Lakes, 1992). Greater success was gained through a combination of thermal softening and high hydrostatic pressure (Martz et al., 1996). A heat of 110°C over 10 hours followed by the continuation of pressure for a further six hours after cooling resulted in a NPR in one axis of closed cell polyethylene foam. Heating the same foam for an hour at 86 °C before subjecting it to a vacuum pressure for five minutes also produced uniaxial NPR.

Recently, there has been greater success in producing auxetic closed cell foams through a steam penetration process (Fan et al., 2018). The foam samples are immersed in water, covered before being subject to experimental heating processes of 100 °C, 80 °C and 60 °C each for 6 hours. The foams are then cooled through which steam condensation forms causing the foams to shrink. The highest temperature resulted in the most effective result, while at 60 °C water struggled to penetrate the cell walls and there was less deformation. The development of NPR closed cell foams offers greater potential in the application of auxetic structures for sport PPE in future research.

2.3.6 Applications of Auxetic Structures in PPE and Sports Apparel

Recent attempts to exploit auxetics for protection and fit in sports apparel have been successful through in plane geometrical arrangements. The upper exterior of a trainer was designed to incorporate printed PU auxetic shapes in order to exploit synclastic curvature and biaxial expansion for improved flexibility during movement (Toronjo, 2013). Additionally, an auxetic rotating triangle structure on the outsole of a trainer (Cross et al., 2015) enabled biaxial growth through wearer movement. Closed-cell foam pads with embossed segmentation of an auxetic re-entrant structure have been incorporated within the D30 (2018) trust helmet pad system, the foam pads are said to provide enhanced fit properties and deceleration under impact. Additionally, D30 (2015) technology has been developed as sPPE for an American football top. The pads are lightweight and flex with the body due to the moulded feature of a re-entrant repeated pattern, although the auxetic effect does not offer through-the-thickness NPR behaviour.

Currently, the auxetic effect is only used in sports apparel in-plane (Toronjo, 2013; Cross et al., 2015; D30, 2018), to enhance fit and comfort. Brands have not yet developed protective equipment that exploits through-the-thickness NPR to reduce peak forces under impact. Interest in the potential of auxetic sPPE has grown, the US Navy have identified the benefits of auxetic fabric for military PPE and commissioned further research into the application (Blacker, 2012). However, optimising processes of fabricating auxetic closed cell foams will improve the route to utilising auxetic foams as sPPE (Fan et al., 2018). In addition, increase in tensile strain decreases NPR and associated effects (Yang et al., 2013) yet it is unknown whether exploiting auxetic structures for synclastic curvature and biaxial expansion will affect impact protection of sPPE. Therefore, determining how auxetic structures can be tailored for the application of sPPE will also improve the potential for pad designers to utilise them commercially.

2.4 Chapter Summary

Rugby shoulder padding design is challenged by providing levels of protection without interfering with player mobility and comfort. EVA currently used for rugby shoulder padding provides poor conformability (Griffiths, 2009), is unable to extend (Borreguero et al., 2012), which could affect user comfort and restriction of body movement during wear. Rugby sPPE discomfort has been identified as the main reason for poor user uptake in a user perception survey (Finch et al., 2001), but shoulder padding was not assessed. The World Rugby Body Padding Specification (2019b) stipulates that shoulder pads must not interfere with player comfort or mobility yet only impact test methods are required in performance assessments. However, performance assessments of comfort and fit have been conducted for other types of sPPE through pressure comfort analysis (Webster and Roberts, 2009) and fit assessments involving active positions (ASTM, 2018). Additionally, there is a lack of research into the effects of different types of padding segmentation types despite the wide commercial variety. Strategies for enhancing rugby shoulder padding must first determine user perceptions of the product as well as performance assessments of its comfort and fit.

Research of 3D printed and textile auxetics have shown that adapting geometry of an auxetic structure can manipulate the auxetic effect including lateral expansion and curvature to domed surfaces (Wu et al., 2018). Additionally, auxetic foams at present do not have suitability to sPPE as further research is required to optimise these materials and respective production processes (Duncan et al., 2016; Fan et al., 2018). Conventional foams can be cut-segmented and molded with auxetic structures to exploit conformability benefits such as synclastic curvature and lateral expansion. However, it is unknown whether exploiting auxetic structures for synclastic curvature will affect the impact protection of sPPE. The auxetic effect has been exploited in sports apparel for enhanced fit and comfort but strategies for the design of sPPE and rugby shoulder padding with auxetic structures remain unknown. The originality and value of this research is in investigating the relationship between auxetic geometries and sPPE conformability.

3 Methodology and Methods

3.1 Research Methodology

The chapter outlined a methodological framework and the strategies employed to realise the research objectives. The research methodology specified the ethical implications associated with the methods as well as the perspectives and philosophies adopted to undertake them. The limitations of each research phase have been assessed and related to the framework employed, researcher's skills or facilities and time where appropriate. Research perspectives and philosophies adopted in the work have been justified in relation to current research of a similar nature. The methodology defined the approaches required to undertake the research. This section outlines the methods of data collection applied to realise the research objectives and these methods include a user perception survey, pressure comfort and garment analysis as mechanical testing.

3.1.1 Research Perspectives

The philosophical perspective that guided the research was Pragmatism. Within Pragmatism, theories or beliefs are evaluated in terms of the success of real world applications (Schonheyder and Hordby, 2018). The pragmatic perspective was critical to determining how to enhance the comfort of rugby shoulder padding by conducting user perception surveys and physical tests (Goldkuhl, 2004). Development of sPPE with auxetic structures also required assessment through a series of physical tests in order to produce implementable findings for future auxetic pad design (Mander, 2008). This perspective enabled the development of the research methods.

Pragmatism

User centred design and research is fundamental to pragmatism, through which the relationship between human beings and reality are under constant physical change (Rylander, 2012). One of the leading contributors to Pragmatic thought, John Dewey, argued that knowledge could only be understood in relation to its context, situating everything (Stromnes, 1991). As such, functional design was identified as an extension to the ideas of pragmatism. The research identified with finding solutions to wearer-issues of current rugby shoulder padding, it was considered a real-world scenario rather than theoretical. Therefore, pragmatic approaches appropriately underpinned the research methods toward a strategy for designing sPPE with auxetic structures.

In pragmatism, inquiry has been used as a tool for transforming problematic situations through considered thought, leading to action, change or development (Capp, 2019). As such gaps in knowledge identified through the literature review regarding the design of sPPE and auxetic structures formed starting points for inquiry. The research was not required to find absolute truths but instead resolutions to the design problems and gaps in research. The findings were intended to contribute to knowledge of how auxetic structures can enhance the conformability of rugby shoulder padding. Therefore, the methods used to address the real-world problem in this research led to working solutions to aid future research and development.

Scientific research methods are integral to pragmatism, in particular where it leads to legitimate and useful findings (Mander, 2008). Therefore, research objectives were generated towards producing practical design strategies and scientific quantitative research methods were applied to do so including surveys and physical testing. Through scientific pragmatism, the research methods were designed to confirm and build upon or reject claims identified through the literature review regarding rugby padding and the potential of auxetic structures.

The outcomes of the research contributed to knowledge based on the specific methods employed. Although, consistency was critical of the methods to ensure trust-worthy findings which would display pragmatic and scientific research ethics (Sutter and Cormier, 2012) that would contribute to knowledge of sPPE with auxetic elements.

3.1.2 Methodological Framework and Research Strategy

The methodology was influenced by previous research into auxetic structures and assessments of sports apparel. Due to limited research into conformability of auxetic structures applied for rugby shoulder padding, new or adapted methods were required. Methods were adapted from standard test methods where possible. The methods were associated with both apparel practices and engineering/material science. Therefore, the methodological framework had an interdisciplinary approach to meet the research objectives:

Objective 1: To critically evaluate literature pertaining to garment technology and wearer issues in padded sportswear and identify suitable auxetic structures and fabrication methods for application as sPPE.

Objective 2: To analyse commercial rugby shoulder padding in relation to the comfort requirements of sporting participants.

Objective 3: To apply auxetic patterns to sPPE through cut-segmentation and evaluate the effectiveness of the developed auxetic sPPE through impact tests under synclastic curvature and analyse pressure comfort and lateral expansion.

Objective 4: To determine design parameters for the most suitable auxetic impact protective material (identified through objective 3), through manipulating scale, gradient and shape.

The multiple pragmatic data collection methods deduced survey responses; rugby participant body scan data and sPPE dimensions; as well as pressure comfort measurements and impact forces. Analysis methods included means, ranges and statistics to produce the data. The research strategy was deductive rather than inductive as the research strategy was built to investigate previous research claims (Rahi, 2017). Prior assumptions were identified through the literature review and then investigated through the research methods. The methods were user-centred to provide new knowledge aimed at informing future pad design.

The research strategy first empathised with the real-world wearer problems of current rugby shoulder padding through a survey and fit assessment. The methods were selected and designed to explore knowledge gaps related to rugby shoulder padding comfort, conformability and perceived protection, identified in Chapter 2. Following the determination that commercial rugby shoulder padding provides poor conformability (Griffiths, 2009) with potential to cause discomfort (Finch et al., 2001), developments of auxetic sPPE were proposed as an alternative solution. Recommendations that auxetic structures could offer an enhanced solution were then considered through a process of development, mechanical testing and validation. The research strategy was devised to determine the parameters to which auxetic structures may pose an enhanced solution to the current state of rugby shoulder padding. The experimental work was conducted through three phases and full ethical approval was sought before commencing the research.

Phase I: User Perception Survey of Commercially Available Shoulder Padded Rugby Tops

To address the knowledge gaps regarding user discomfort of rugby shoulder padding and whether it was a cause for poor uptake, a user perception survey was designed. Phase I was designed to address objective 2 and ensured that the research was pragmatic and not simply theoretical, based on a real-world scenario. An online survey was devised, using an established comfort model to deduct data intended to dispel or support current knowledge of rugby shoulder padding. Respondent criteria was that they had to be over the age of 18 and current participants of rugby Union, sampling was otherwise random. The data was collected in Qualtrics software and statistical analysis was performed using SPSS Statistics.

Phase II: Fit Analysis of Commercial Rugby Shoulder Padding

The methods in Phase II were designed to assess the conformability of different types of rugby shoulder padding, fulfilling objective 2. The research assessed a range of size XL rugby shoulder padded tops featuring different segmentation types that reflected the commercially available variety. There was a focus on menswear rather than women's in this research because Women's rugby shoulder pads extend to include breast coverage (World Rugby, 2019b). However, it was believed that new knowledge informing pad design which enhances conformability to shoulder curvature and movements would be transferrable to other types of sPPE, including Women's rugby shoulder and breast padding. The XL tops were fitted to volunteer participants and the fit was recorded. Data collection included body scan measurements, pressure comfort readings and shoulder padding dimension specifications which were analysed in relation to the effectiveness of different segmentation types.

Phase III: Development of Auxetic Shoulder Padding

Finally, the development and assessment of an auxetic alternative to rugby shoulder padding met objectives 3 - 4. The first stage of Phase III developed rugby shoulder padding with a range of auxetic and one non-auxetic segmentation. The unit cells for segmentation were drawn using Adobe Illustrator and laser cut-segmented before being subjected to mechanical testing. The pattern that led to the lowest peak forces and offered the greatest conformability was manipulated in stage 2 and subject to repeated drawing, segmentation and test methods. The outcomes stipulated how far auxetic structures posed an alternative enhancement to current rugby shoulder padding within the constraints of the research. The methods applied for Phases I – III are outlined in the following section.

3.2 Phase I - User Perception Survey of Commercially Available Shoulder Padded Rugby Tops

Problem Statement

Phase I was designed to assess the prevalence of shoulder padding use and comfort perceptions among a sample of current rugby players. User discomfort has not yet been investigated for rugby shoulder padding in detail, yet discomfort is claimed to be the primary reason for inhibiting the use of PPE (Kajtaz and Subic, 2019). Previous sport PPE surveys that determined user perceptions through survey questionnaires (Finch et al., 2001; Braham et al., 2004) identified motivating factors for its wear. A questionnaire survey was therefore a suitable approach and a recognised tool for exploring, explaining and evaluating people’s attitudes, behaviour and opinions (Flynn and Foster, 2009). Determining user comfort perceptions of rugby shoulder padding informed future design tailored to improve wearability. This research partially addressed objective 2 of the PhD to analyse rugby shoulder padding in relation to participant comfort requirements, as follows:

1. To establish which participants wore shoulder padding.
2. To establish how critical shoulder padding was to user perceptions of safety and protection.
3. To establish reasons for the wear of shoulder padding.
4. To determine rugby participants comfort requirements for shoulder padding.

Online Survey

Approximately 4 billion people in the world now have internet access (Onireti et al., 2016), making online surveys a fast and inexpensive route to distributing to and collecting respondents (Dillman et al., 2009). Other researchers have implied that online surveys can lead to biased samples of respondents neglecting participants that are harder to reach online, including the young and elderly (Horevoorts et al., 2015). Online surveys have also been found to retrieve a lower response rate than questionnaire surveys conducted postally or face-to-face (Petchenik and Watermolen, 2011). However, online surveys distributed to participants by email enabled higher response rates (Ilieva et al., 2002). Online software, Qualitrics, was identified as the best route to conducting the questionnaire survey.

The survey design used quantitative closed-ended question types; alternatively answers to open-ended questions provide difficulty in coding as they may require interpretation (Fink, 2015). Online surveys are recommended for obtaining and processing data from close-ended questions (Gratton and Jones, 2010), question and answer formats are easy to replicate and follow. Qualtrics was set up to automatically delete incomplete responses, saving time and preventing human error by manually removing respondents that gave incomplete answers. The software used for the survey also processed and organised the data automatically for analysis externally on SPSS. Therefore, an online survey was a suitable method for exploring user perceptions of rugby shoulder padding.

Survey Design

Previous research into user perceptions of sport PPE comfort have been explored through a comfort model: fit, protection, thermal, sensorial, weight and aesthetic (Webster and Roberts, 2009). The comfort model was deemed transferrable for the exploration of rugby shoulder padding comfort in Phase I. To address the objectives for Phase I survey question themes were developed: demographics, product use, injury, behaviour and attitude. The demographic questions formed the independent variables in the survey, whereas questions under the remaining four themes defined dependent factors. The purpose was to distinguish relationships between the independent and dependent variables. The survey questions can be found in Appendix A.

The survey themes were spread across a total of ten close-ended questions. The short survey was chosen to reduce respondent fatigue, enabling a higher rate (Crawford et al., 2001) and quality (Dolnicar et al., 2011) of response. The survey questions were categorical (nominal and ordinal). Categorical variables could be divided into distinct categories whereas continuous variables were those scored distinctly (Field, 2013) and therefore dependent on the nature of the questions. All background (demographic) questions were categorical whereas questions under the remaining themes were a mixture of categorical and continuous. Distinguishing between variable types was critical for determining suitable analysis methods.

The background questions formed the independent variables in the survey as they were used to classify the sample (Salkind, 2010). Gender, age, rugby training level and rugby playing position were chosen as the demographic questions for Phase I. Gender was critical to the background of the sample as rugby shoulder padding can be sold as gendered garments for men and women (Brisbine et al., 2019). Research has linked higher injury risks in rugby to higher age and training level of players (Williams et al., 2013). Therefore, age and training level were also important to determining the sample background.

Playing positions were deemed necessary to distinguishing between the sample as different playing positions are exposed to different injury patterns (Swain et al., 2016). Ten possible player positions were used for this survey, even though there are fifteen playing positions in rugby Union (Cahill et al., 2012). The positions were reduced by grouping Left and Right wing as Wing, Inside and Outside Centre as Centre, Blind-side and Open-side flanker as Flanker and finally, Loose-Head and Tight-Head Prop as Prop. It was possible to group similar positions to encourage a more even distribution of answers from the sample of respondents. This technique was of benefit as a route to reducing the respondents' survey fatigue (Story et al., 2019).

Likert scales and rank orders are encouraged for use as close-ended questions in user perception surveys (Fink, 2015). Likert scales have most popularly been used in previous user perception surveys of sports PPE (Akenhead and Nassis, 2016) and therefore they were used predominantly in Phase I. Question answers representative of the dependent variables utilised Likert disagree to agree interval scales and rank order as the purpose was to measure opinion. Where respondents were asked to rank the answer options, the ranked values ranged from 1st to 6th. Likert scales were used the most frequently in Phase I and to prevent survey fatigue and engage respondents' attention the values were alternated between -2 to 2 and 1 to 5, where '0' presented a neutral response.

After the four background questions, respondents were asked to describe their product use, to establish which participants wore shoulder padding and to what frequency. Product use could then be contextualised with reasons thought to affect its wear in questions 6 – 10. Question 6 asked how far respondents felt that shoulder padding had helped to protect them against four types of injury, increasing in severity. Question 6 was designed to identify how critical shoulder padding was to rugby Union participants perceptions of safety and protection. This question was selected based on previous research which has claimed that a lack of belief in the protectiveness of PPE has prevented its wear (Finch et al., 2001).

Questions relating to behaviour were intended to draw out respondent circumstance relating to the wear of shoulder padding. It had been suggested that rugby playing peers have not previously encouraged the wear of PPE, investigated through question 8. Whereas question 7 asked how far the wear of PPE had affected participants' comfort, to then compare which had a greater effect on choice to wear. Attitude questions were placed at the end of the survey questionnaire because attitude is influenced by context (Pienaar et al., 2013); questions 9 and 10 sourced user opinions of comfort. Question 9 asked whether shoulder padding met respondent comfort needs and question 10 which of the same comfort factors was more important to the buying decision, as a form of triangulation (Fielding, 2012).

Five hypotheses were required to define the relationship between the independent and dependent variables in the survey, as shown in the analysis plan (Table 2). The respondents were divided by the groups they were classified by, i.e. female and male; this data was then tested against the dependent variables to identify whether background affected user perceptions of shoulder padding. Each hypothesis was tested once to prevent type I or type II error. Type I error occurs when the null hypothesis has been rejected even though it is actually true and conversely type II error results from accepting the null hypothesis when it is actually false (Banerjee et al., 2009). When the null hypothesis was rejected, the alternative hypothesis was accepted due to the process of exclusion, conversely the alternative was to reject this upon acceptance of the null hypothesis.

Table 2: Analysis plan

Null hypothesis	Research Hypothesis	Independent variable	Dependent variable	Analysis method
There will be no difference in the choice to wear PPE of participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. There will be a difference in choice to wear PPE of participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. Nominal 2. Ordinal 3. Ordinal 4. Nominal	Scale: Frequency of wearing PPE (Q. 5)	1 - 3. Sig: ANOVA/ Kruskal- Wallis. Measure of association: Gamma. 4. Sig: T-test/ Mann- Whitney. Measure of association: Contingency coefficient/ Cramer's V
There will be no difference in beliefs of PPE protection by participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	There will be difference in beliefs of PPE protection by participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. Nominal 2. Ordinal 3. Ordinal 4. Nominal	Scale: protection against four types of injury (Q. 6)	1 - 3. Sig: ANOVA/ Kruskal- Wallis. Measure of association: Gamma. 4. Sig: T-test/ Mann- Whitney. Measure of association: Contingency coefficient/ Cramer's V
Encouragement to wear PPE will not be dependent on participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	Encouragement to wear PPE will be dependent: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. Nominal 2. Ordinal 3. Ordinal 4. Nominal	Scale: Encouragem ent from family, team members and coach (Q. 8).	1 - 3. Sig: ANOVA/ Kruskal- Wallis. Measure of association: Gamma. 4. Sig: T-test/ Mann- Whitney. Measure of association: Contingency coefficient/ Cramer's V
PPE comfort will not be dependent on participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	PPE comfort will be dependent on participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. Nominal 2. Ordinal 3. Ordinal 4. Nominal	Scale: Effect of PPE on comfort (6 realms) during play. Q. 7	1 - 3. Sig: ANOVA/ Kruskal- Wallis. Measure of association: Gamma. 4. Sig: T-test/ Mann- Whitney. Measure of association: Contingency coefficient/ Cramer's V
PPE will not meet participant needs dependent on their: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	PPE will meet participant needs dependent on their: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. Nominal 2. Ordinal 3. Ordinal 4. Nominal	Scale: Comfort requirement s (6 realms) (Q. 9)	1 - 3. Sig: ANOVA/ Kruskal- Wallis. Measure of association: Gamma. 4. Sig: T-test/ Mann- Whitney. Measure of association: Contingency coefficient/ Cramer's V
Prioritisation of comfort realms will not be dependent on participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	Prioritisation of comfort realms will be dependent on participants: 1. Training levels 2. Playing positions 3. Age groups 4. Genders	1. Nominal 2. Ordinal 3. Ordinal 4. Nominal	Scale: Most important factor of comfort (6 realms) influencing purchase of PPE (Q. 10)	1 - 3. Sig: ANOVA/ Kruskal- Wallis. Measure of association: Gamma 4. Sig: T-test/ Mann- Whitney. Measure of association: Contingency coefficient/ Cramer's V

SPSS was used to both manage and interpret the data which was analysed at a univariate and bivariate level. SPSS automatically set the confidence interval at 95% for analysis, to ensure confidence in the sample. Univariate analysis was intended to summarise and scrutinise the data obtained for each variable independently (Field, 2013); whereas bivariate analysed one independent and one dependent variable, as shown in Table 2. Finally, a series of parametric assumptions had to be met to run parametric tests on the data, applying to data established as having approximately normal distribution and homogeneity of variance. Where the parametric assumptions were not met non-parametric tests were ran instead.

Sampling Strategy

The survey used a mixture of purposive and volunteer sampling strategies to reach male and female rugby union participants, over the age of 18. Typically, power sample size calculations are required to determine a reliable sample size, proportional to the target population and avoid error in doing so (Ryan, 2013). In a power sample size calculation, the confidence interval is directly proportional to the sample size such that a 95% confidence interval, allowing for a 5% error margin, is indicative of a larger and more rigorous sample, reflective of the population (Jones et al., 2004). However, error margins of between 5% and 10% are deemed rigorous for statistical analysis (Harrison et al., 2020). Therefore, based on a population of 9.6 million rugby participants (World Rugby, 2018) and error margins of 5% and 10%, a sample size was calculated as requiring 97 – 385 participants. However, in accordance with the time-line for Phase I, the responses were to be capped after three months provided the responses reached the minimum of 97 participants, the minimum margin for error.

Participant Information, Consent and Distribution Channel

Upon entering the online survey its contents and purpose were summarised. The participant information also declared that respondents could opt out at any time and incomplete surveys would be automatically deleted within the Qualtrics software. Participants details were anonymised within the software such that this information was unknown even to the researcher. Survey data was to be stored by Manchester Metropolitan University on a locked computer for up to five years and then destroyed. The researchers details were shared with the participant such that they could ask further questions about taking part in the study. Online distribution was also employed, offering the potential to gain a wider geographic sample across distant locations that might normally be both time-consuming and difficult to reach. Online distribution via social media enabled the recruitment of an international sample with more ease than traditional recruitment methods (Branley et al., 2014).

Data Management

Once the raw data had been collected, it was necessary to re-code answers to background questions that received an unbalanced representation. Where answer categories to a question were limited and it was possible, such as for age, categories were collapsed and given a larger regrouping. Table 3 shows the answers which were re-coded to produce less answer categories, with the aim of being able to make inferential claims about the sample. In order to re-code question 3 the ten playing positions were instead collapsed into three groups which showed exposure to tackles. It was then possible to determine whether exposure to tackle significantly affected product uptake.

Table 3: Re-coding of the survey

Questions requiring re-coding	Answer options	Re-coding	Reason for re-coding
Q. 1 What is your age?	18 - 24, 25 - 34, 35 - 44, 45 – 54, 55 – 64, 65 – 74, 75 years or older, prefer not to answer	18-24, 25-34, 35+ (all groups in 35 plus years)	Categories including the ages 35-75+ received fewer responses.
Q. 3 What position do you play in rugby Union?	Wing, centre, fly-half, scrum-half, number eight, flanker, hooker, prop, 2nd row, full-back	Position exposed to: Least tackles (wing, fly-half, scrum half, full-half), a mid number of tackles (prop, hooker, centre), most tackles (flanker, 2nd row, number 8)	To group and relate positions to levels of danger.
Q. 4 What standard do you play rugby to?	Recreational, competitive, semi-professional, professional	Recreational, competitive, professional levels	Semi professional and professional levels received fewer responses.

3.3 Phase II

3.3.1 Pilot Study: Characterisation of Rugby Shoulder Padded Tops

The pilot study analysed the fit of commercially available rugby shoulder padded tops to one size XL male participant, whose chest fitted within the measurement range for a size XL. Five commercially available men's rugby shoulder padded tops (appendix D) were selected for analysis. Menswear was chosen rather than women's because the womenswear shoulder pad protection market largely consists of padding that extends to the chest in order to protect breast tissue. It was identified that by initially focusing the research on a smaller, curved body region, the findings would benefit the enhancement of both men and women's protective wear. The objectives of the study were as follows:

1. To establish the fit issues common to all rugby shoulder padding.

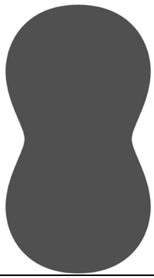
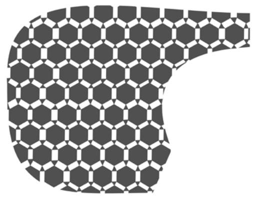
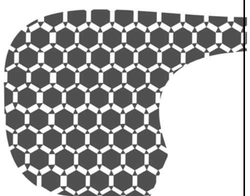
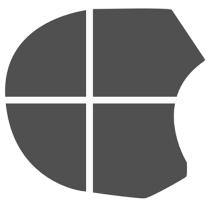
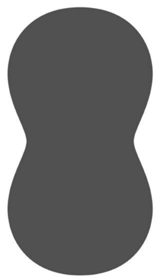
2. To identify how different designs of rugby shoulder padding correspond to various fit issues.
3. To determine which rugby shoulder padding type enabled the greatest fit.

Garment fit was analysed in relation to the respective technical specifications, and can be found in Appendix D. The technical specifications included a construction method, componentry list and measurement chart. To gain an accurate profile of each rugby shoulder padded top, technical drawings were also created to coincide with the technical specifications. Measurements provided by the technical specification added quantitative value to the fit assessment that was otherwise largely subjective, based on observation. The overriding objective of the pilot study was to profile the fit issues associated with the different types of rugby shoulder pads and those common to all.

Garment Selection

The commercially available, IRB approved shoulder padded rugby tops chosen for the pilot study were required to reflect the market variety. The study benefited from a Manchester Metropolitan University bursary, granting the purchase of five representative tops, two of each. The literature review market research identified that current shoulder padding varied by shoulder coverage and segmentation type as shown in Table 4. Shoulder padding varied by coverage due to the World Rugby Body Padding Specification (2019b) that stipulated only the maximum protected region and reducing coverage can enhance conformability (Barbour, 2014). Regulation 12 (2012) also outlined that shoulder padding should not restrict normal playing movements, hence a variety of segmentation techniques exist, attempting to decrease the hindrance and discomfort caused by wearing bulky padding.

Table 4: Shoulder padding segmentation and coverage variety

Segmentation		Coverage (Size and Shape)	
Type	**Example**	**Type**	**Example**
1. None	Optimum Tribal Five Pad 	A. Monopad (shown halved)	Canterbury Vapodri Raze Pro 
2. Cut segmented	Canterbury Vapodri Raze Pro 	B. Extends to upper arm	Gilbert Triflex XP1 
3. Vacuum moulded	Gilbert Triflex XP1 	C. Contoured Collarbone	Kooga IPS V 
4. Segmented	Canterbury Vapodri Raze 	D. Minimal contouring	Optimum Tribal Five Pad 

The shoulder padded tops selected for the pilot study were required to reflect the variety identified through market research conducted in Chapter 2. Selection criteria for the five tops ensured that each top represented a unique combination of the segmentation and coverage types. All the segmentation and coverage types had to be seen across the five garments, outside of that criteria the garments had to be a UK Men's size XL. The garments were otherwise selected based on the bursary budget and therefore sampling was a mixture of purposive and random. Figure 26 shows the rugby shoulder padded tops that were selected, including its segmentation type number and coverage type letter from Table 4.

4D) Canterbury Vapodri Raze

2A) Canterbury Vapodri Raze Pro

3B) Gilbert Triflex XP1

3C) Kooga IPS V

1D) Optimum Tribal Five Pad

Figure 26: The five shoulder padded rugby tops (Authors Own Image, 2017)

Fit Model Sample Strategy

In 2015 the average weight of England rugby players that participated in the World Cup was 101kg; the lowest player weight was 84kg and the highest was

115kg (Rhodes, 2015). The players all came in over 6ft with the highest player reaching 6ft 6inches (World Rugby, 2015). It has been identified that rugby players are becoming more powerful due to increased weight and height. Therefore, the selection process for the fit model involved identifying a current participant of rugby Union, whose height was between 6 and 6.6ft, with a weight between 84 and 115kg. The model selected was as follows:

- Weight - 114kg
- Height - 6ft.6inches
- Position – Prop
- 28 years old
- Identified through word of mouth: Garments were first obtained and then fitted to a range of size XL fit models who fit the remaining criteria; the rugby player with the best fit was identified.
- Full ethical approval was sought.

Data Collection

Each garment was deconstructed to obtain its construction method; measurement charts and garment technical drawings were also produced. As two of each garment was purchased, the second was used for a fit assessment with the chosen model. The information obtained for each garment was reported in appendix D. The garment specifications were collected to provide context for the fit assessment. Understanding the make up of the garments was considered an ideal starting point for assessing effect on quality of functionality and fit (Bell et al., 2018).

Documentation of Garment Appearance

The five garments were drawn using Adobe Illustrator CC (Adobe Systems Incorporated, USA) as reference for the measurement chart, the two are presented together in Appendix D. Drawing the garments was deemed more suitable than taking photographs of them on a flat surface to clearly show stitch types and seam positions. Images of the five garments were also taken on a size XL Alvanon soft series mannequin (AVF 19921/40). The photographs were taken for permanent documentation of the garments in a consistent and clear format. The photographs were used as a reference in Figure 26.

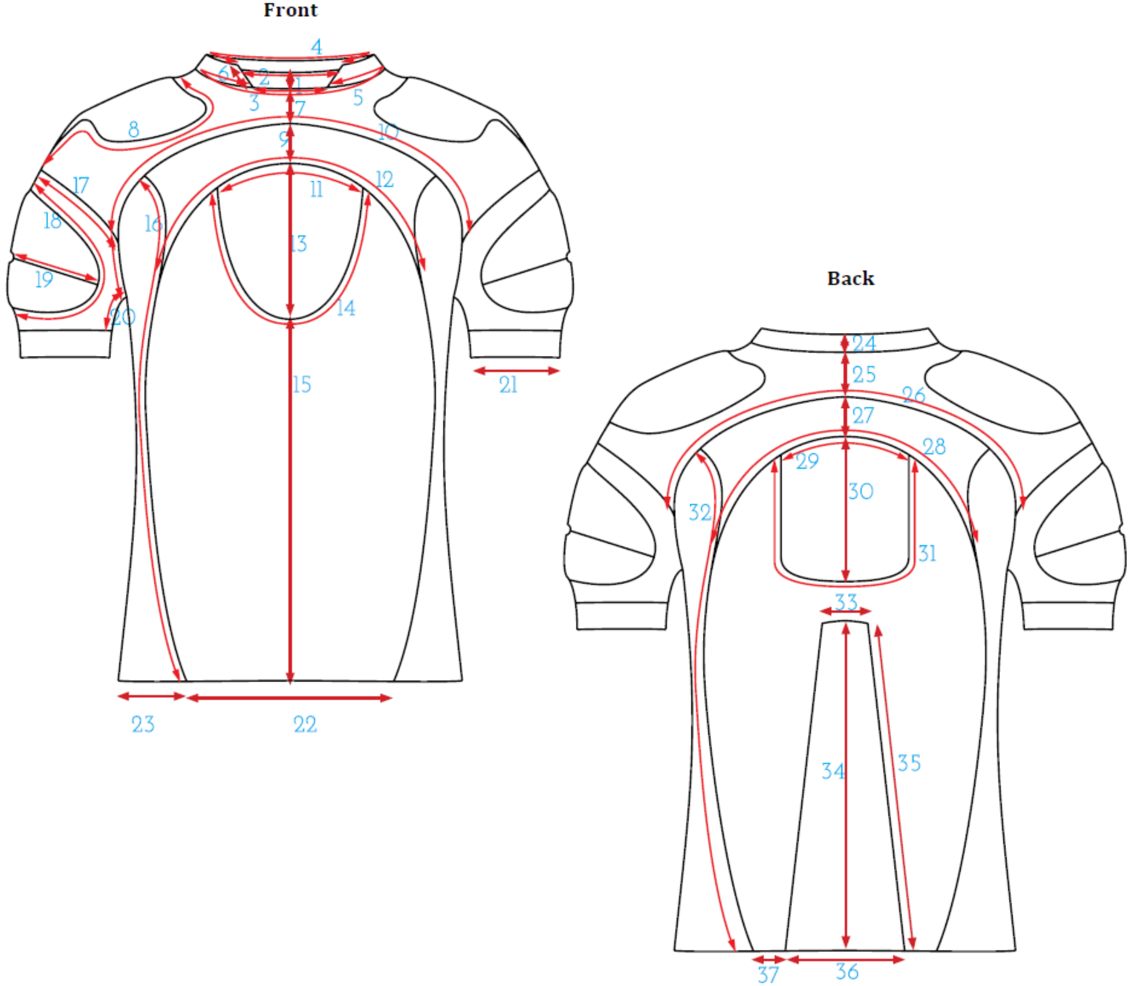
Measurement Chart

The garments were placed on a flat surface so that they were not subject to stretch when manual measurements were taken according to previous methods for recording garment dimensions (Myers-McDevitt, 2004; Bubonia, 2014). It was decided that every panel within the garment would be measured, providing a wealth of data. In addition, specifications for garment measurement charts (Zakaria, 2014) have indicated that the centre front and centre back are critical garment measurements. Therefore, the number of measurements taken from each garment was dependent on the number of panel pieces within that top. The most critical measurement was considered the shoulder pad circumference as it outlined the shoulder coverage of each pad. The measurement chart for Gilbert Triflex XP1 is shown in Table 5.

Table 5: Gilbert Triflex XP1 measurement chart

No.	Position on the garment	Measurment (cm
1	Centre front neck panel depth	2.0
2	Centre front upper neck panel width	11.0
3	Centre front lower neck panel width	9.5
4	Outer neck panel upper width	34.0
5	Outer neck panel lower width	39.0
6	Outer neck panel diagonal side seam	3.0
7	Centre front shoulder panel (vertical)	7.0
8	Circumference of shoulder pad	76.0
9	Centre front chest panel (vertical)	6.0
10	Chest panel upper seam (horizontal)	137.0
11	Protective chest pad cover upper seam (horizonta	18.5
12	Chest panel lower seam (horizontal)	41.0
13	Protective chest pad cover depth (vertical)	18.0
14	Protective chest pad cover lower curve (horizonta	39.5
15	Centre front body depth (vertical)	40.0
16	Front side panel (vertical)	65.7
17	Over shoulder (horizontal)	48.4
18	Protective arm pad cover cirumference	81.0
19	Protective arm pad centre seam (horizontal)	35.8
20	Inside arm seam	14.0
21	Arm hole width	33.0
22	Centre front panel hem	20.0
23	Side panel hem	32.0
24	Centre back neck panel depth	3.0
25	Centre back shoulder panel depth (vertical)	11.5
26	Centre back shoulder panel lower edge (horizont	55.5
27	Higher back panel depth (vertical)	6.0
28	Higher back panel lower edge (horizontal)	38.5
29	Protective back pad cover upper edge (horizontal	15.5
30	Protective back pad cover depth (vertical)	16.5
31	Protective back pad cover lower curve	41.5
32	Back side panel (vertical)	65.5
33	Lower back panel upper width	5.5
34	Lower back panel depth	37.0
35	Lower back panel side seam	38.0
36	Lower back panel hem (horizontal)	14.5
37	Back panel hem width	2.0

Technical drawing



Construction Method

The deconstruction of one copy of each top provided a reverse order understanding of the construction methods (Bubonia, 2014). Through the process, the sewing machine stitch type, seam allowance and construction operation were recorded in the logical order. The seams used for the construction of the five garments were identified as overlock, flatlock and adhesive (Beaudette and Huiju, 2016). The seam types were used as a reference for the measurement chart and the technical garment drawings. The construction methods also provided contextual information for the fit assessment where it was necessary to describe seam positioning. The construction method was documented in a table format and can be found in Appendix D.

Fit Assessment

Protective garment fit has previously been assessed through body positions that mimic those of the respective sporting tasks (ASTM, 2018). The moving body positions are referred to as active positions (Braganca et al., 2016) and a standard for the fit assessment of rugby Union shoulder padding does not yet exist. Therefore, suitable active positions were identified for use in the pilot study fit assessment. The fit assessment was conducted with the model's arms first in a relaxed pose, by his side; as well as arm raised level with the shoulder, both out to the side and forward. The positions were chosen based on arm raises required during rugby Union tackling and scrummaging (World Rugby, 2014) in order to show how fit would be affected during movements related to rugby participation.

The five garments were designed by four sportswear brands. As such the dimensions of the garments reflected four different men's size XL body types and regions of shoulder pad coverage. Therefore, it was likely that the overall garment fit to the size XL model would vary between garments. The fit assessment had a greater focus on conformability of the padding to the shoulder region than of total garment fit. The fit analysis was documented with pictures which aimed to gain a total perspective of the shoulder padding, including front, back and side views.

3.3.2 Fit Analysis of Current Rugby Shoulder Padding

Phase II focused on the conformability of nine Rugby shoulder pads, analysed through a fit assessment and pressure comfort analysis. Pressure comfort analysis has been used to measure the pressure (mmHg) generated at a region of the body due to garment wear (Senthilkumar et al., 2012). Therefore, determining the pressure generated through shoulder padding wear provided an understanding of its effect on body comfort. Pressure comfort has been neglected in previous assessments of closed cell foam body padding but has been used in the comfort analysis of cricket leg guards (Webster and Roberts, 2009) which have a hard-outer shell. Phase II addressed objective 2 of the research to analyse current rugby shoulder padding for rugby through fit and pressure comfort assessments, as follows:

1. To determine how far current shoulder padded rugby tops provide good pressure comfort through a fit assessment and pressure comfort analysis.
2. To establish the fit issues common to all rugby shoulder pads.
3. To identify how segmentation techniques used for shoulder padding led to different fit issues.

The nine shoulder protective rugby tops obtained were all a Men’s size XL, as justified for the pilot of Phase II. Four of the garments used for the pilot study were in the same condition they were bought in and therefore were used again for the study. The research benefited from an additional five tops donated by brands Body Armour, Canterbury and Gilbert to the Manchester School of Engineering. Therefore, the selection process used for the pilot study was not repeated. All of the shoulder pads were 1 cm thick.

The size guides for a Men's XL varied between the five brands and the variety can be observed in Figure . All brands provided a chest measurement range recommendation for the XL tops, Canterbury was 109 – 114.5 cm; Gilbert indicated 107 – 113 cm; Kooga had 110 – 115 cm; Body Armour's was 112 – 117 cm. A chest circumference range of 107 and 115 cm was suitable for all the tops which the participants chests were required to sit within. As the study focused on menswear, participants were required to be male and over the age of 18. Participants were recruited from Manchester Metropolitan University (MMU) rugby team for ease, and all size XL players were invited to volunteer, sampling was a mixture of random and purposive (Jupp, 2006).

Figure 27: The nine garments selected for the study (Authors Own Image, 2017)

The suitability of each size XL top to the six participants was determined by comparing garment chest circumference ranges to the participants. A full body surface scanner (Size Stream Body Scanner v16.0, Cary, NC, USA) measured the participants in the Innovation Zone at Manchester Metropolitan University. The body scanner captured 53 landmarks across the full body, although the axilla chest circumference was used as the landmark for indicating fit suitability. The body scanner also created a data map of the body with the fit models in close fitting underwear, so to display their true measurements. The image created of the body data map was then used as a reference for the participant's body shape.

Participant Information and Consent

Volunteers were provided with a participant information form upon arrival. They were given the opportunity to raise questions or opt out of participation. Those that chose to take part then signed the consent form outlining the data protection, their rights and that they could withdraw at any point during the study. Participants faces were not included in photographs to protect their identity and they were coded by number rather than name for this reason also. Participants received an additional consent form on behalf of the Manchester Metropolitan University Manchester Fashion Institute and their demographic information was recorded and their consent was coded to ensure privacy.

Pressure Comfort Measurements

Pressure comfort was measured (mmhg) using a 50 mm diameter PicoPress sensor (PicoPress M-677, Microlab, Padova, Italy). The Picopress sensor has been regarded accurate and repeatable by some researchers (Partsch et al., 2006; Schuren, 2014; Rahimi et al., 2016) but less so by others (Khaburi et al., 2011; Lao et al., 2019). In addition, body padding has been found to move out of position during movement (Jewell et al., 2006). Therefore, three measurements were taken at each landmark and the mean was calculated for reliability. The sensor was placed flat between the skin and each garment by hand and measurements were taken to the nearest 1mmHg.

Both a front and back shoulder landmark were measured using the PicoPress sensor for comparison. The shoulder landmark was identified on each participant as 3 cm below the meeting point of the Clavicle and Acromion shown in Figure 28, at the front and back of the shoulder. The landmark was chosen for study as it sits at the top of the shoulder, from which abduction, adduction, rotation, circumduction and flexion happen. Therefore, the landmarks had great exposure to the dynamic shoulder movements under assessment in the study.

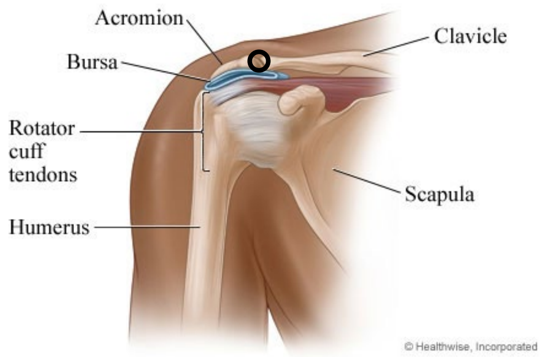


Figure 28: Front landmark of a shoulder region marked by a black circle

Three main positions were derived from the range of shoulder movements required for performing rugby tasks. The identified positions were arms raised to the side, mid height (a), arms raised forward, to a mid-height (b) and overhead (c) as seen in Figure 29. A stationary position with arms relaxed by the participants side was also used to reflect the body position between movements. The six participants assumed the four active and stationary positions in each of the nine tops; the front and back pressure comfort measurements were taken three times in each. Analysis of the pressure comfort data was conducted by comparing means and range of means between the front and back, and across the four positions.

a) side, mid height b) forward, mid-height c) over head

Figure 29: Arm positions during a) maul, b) side-on shoulder tackle and c) ruck (World Rugby, 2014)

Elastane enables medical and sports compression garments to transfer benefits to the wearer, as rugby shoulder pads are without elastane, medical and sports compression grade pressure values were deemed to be too high. Light medical elastic compression has been defined as 10-14 mmHg, mild as 15-21 mmHg and 23 - 49 mmHg ranges from moderate to very strong (Lymed, 2020). The lowest pressure reported at the shoulder region of a commercially available sports compression top was 3.2 mmHg (Brubacher et al., 2017), although it was not identified whether that pressure level would distribute any benefits to the wearer. Therefore, 3.2 mmHg was considered above the pressure range that should be obtained for rugby shoulder padding. Finally, ‘0 mmHg’ pressure comfort revealed loose garment fit; it quantified that the shoulder padding sat away from that shoulder landmark.

Fit Assessment

The fit assessment used the same process purposed for the pilot study. However, in contrast to the pilot, the Phase II fit assessment was conducted on the participants in one position, stationary, rather than active positions too. Fit assessments through the chosen active positions were not found to lead to rich data for analysis in the pilot. Pressure comfort analysis was used instead to determine the effect of the shoulder pads on wearer comfort. Therefore, the fit assessment in Phase II observed the overall padding fit and conformability not through body movement and suitability of garment to participant's size.

3.4 Phase III - Development of Auxetic Shoulder Padding

Phase III addressed recommendations (Foster et al., 2018; Zhao et al., 2019) that PPE with auxetic structures exhibiting synclastic curvature and biaxial expansion could provide enhanced conformability to curved body regions. Previous research has shown a variety of auxetic structures under biaxial expansion (Martin, 2011; Cross et al., 2015) and synclastic curvature (Lakes, 1987; Wang and Hu, 2014). However, the effect of impact forces on materials under synclastic curvature and biaxial expansion are not yet known. Additionally, auxetic structures have been found to enable different behavioural characteristics (Elipe and Lantada, 2012). Phase III addressed objectives 3 – 4 of the PhD to apply and manipulate the geometry of auxetic structures to PPE as segmentation and assess the effect on conformability and peak forces, as follows:

1. To apply auxetic patterns, through thickness manipulation on PPE.
2. To identify which auxetic shape had the greatest suitability to rugby shoulder padding through physical assessments of conformability and impact protection.
3. To establish whether tailoring the chosen shape by unit cell scale, cut widths and anisotropy affected the conformability and peak forces under synclastic curvature of the PPE.

The research was separated into two stages using identical assessment methods. The first stage determined the most conformable and impact force attenuating shoulder pad of five different segmentation patterns, including one non-auxetic to demonstrate comparison. The segmentation pattern that enabled the greatest conformability and attenuated the lowest peak forces was then manipulated in stage two. The same assessment methods were used for stage one and stage two, as shown in the Phase III methods flowchart (Figure 30). Phase III ascertained which of five auxetic segmentation patterns and nine manipulations led to the lowest compromise in conformability and impact protection.

Stage 1 – Identify the most suitable auxetic shape for rugby shoulder padding.

Draw auxetic shapes: rotating squares, 4-pointed star, chiral and 3-pointed star as well as non auxetic – honeycomb using Adobe Illustrator CC (22.1) such that each unit cell is comprised of ribs 10 mm long, within a 12 x 12 cm repeated pattern with 1 mm space between unit cells.

Stage 2 – Tailor the identified auxetic shape for enhanced conformability.

Draw the shape identified in stage 1 using Adobe Illustrator CC (22.1) in 9 variations, laser cut widths of 0.1, 0.3 and 0.5 cm; unit cell scales of 1.5, 2 and 3.5 cm; as well as varying increments of anisotropy in the horizontal increasing these ribs by 0, 0.3 and 0.5 cm.

Laser cut (Lotus Laser Systems LL10060, 0.1 mm laser beam) the patterns into EVA foam (Nanan Hongyang, 20kg/m ^{3}; 70% PE, 20% EVA, 7% foaming agent, 2% talcum, 1% colourant), producing 3 samples of each pattern.

Tensile Test: Tensile displacement was recorded three times on the Testometric Micro 500 (15 cm gauge) but lateral displacement at T, M, B was measured manually at maximum vertical extension, identified by audible or visible signs of the EVA foam breaking.

Dimensional Changes: Mark shoulder region of size XL Alvanon soft series mannequin (AVF 19921/40) and pin four corners of EVA pads in place. Place mannequin arm in four arm raise positions, take pictures from different angles of conformability, measure extension/reduction of total pad and of laser cut-segmented regions.

Pressure Comfort: a 50 mm diameter PicoPress sensor (PicoPress M-677, Microlab, Padova, Italy) was placed flat between the pads and front and back shoulder landmarks over the four arm raises, three measurements were taken at each landmark, to the nearest 1mmHg.

Impact attenuation test: use a bespoke drop tower rig with domed striker made to the World Rugby Body Padding Specification (2019b) with both a domed anvil and a flat anvil. Four load cells (208C05-Force Sensor, PCB Piezotronics) were attached to the anvils with a sensitivity of 0.009109 m V/N, as detailed by the manufacturer).

Commence Stage 2 with the best auxetic structure from stage 1.

Best candidate has been identified. Commence Phase IV.

Figure 30: Flowchart of Phase III methods

3.4.1 Part 1 – Determining Behavioural Changes of Auxetic Structures Through Physical Testing

The World Rugby Body Padding Specification (2019b) requirements for shoulder padding indicated that it should not restrict wearer mobility or cause discomfort. Methods of enhancing conformability to the shoulder region have been employed in the design and construction of shoulder padding often through segmentation (Diamond, 2012). Segmentation can reduce material depth at regions where vacuum moulding is used (Berger et al., 2005) and increase porosity where cuts are created (Morrow and Winningham, 2006), typically leading to a trade-off with protective coverage. Therefore, the auxetic structures applied as segmentation for shoulder padding were required to offer the greatest coverage possible. Auxetic structures either protrude from central vertices or they do not; Figure 31b displays an arrow-head auxetic structure which does not protrude from a central vertex.

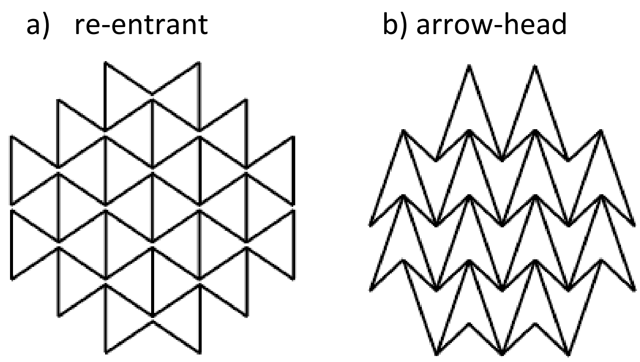
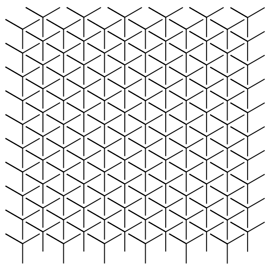
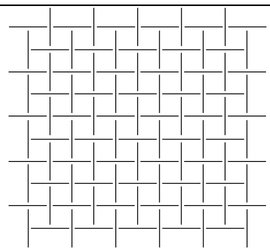
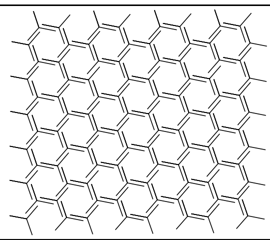
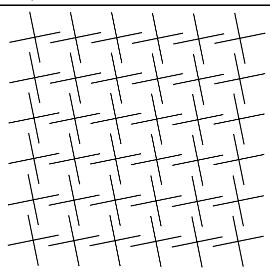
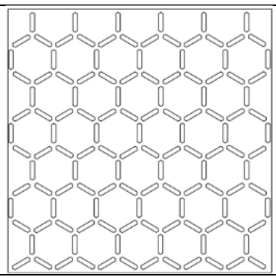


Figure 31: Repeated patterns of auxetic shapes that do not protrude from a central vertex

Phase III stage 1 applied only auxetic structures with unit cells that protruded from a central vertex as segmentation patterns to maximise protective coverage. The chosen auxetic structures included rotating squares, chiral, the three pointed and four-pointed star, as shown in table 6. The chosen shapes were also required to display isotropic NPR, to ensure that structural behaviour would not be affected by orientation. The non-auxetic structure under study was a honeycomb pattern, selected as the Canterbury Raze Pro honeycomb segmented pattern offered the greatest conformability in Phase II. The unit cells of the five patterns were approximately 2.0 x 2.0 cm, with 0.2 cm between each unit cell to match the Canterbury Raze Pro honeycomb repeated unit cells.

Table 6: The five laser-cut segmentation patterns

Patterns	Unit cell	No. sides when opened out
Chiral		6
Rotating squares		4
Three-pointed star		6
Four-pointed star		8
Conventional/ honeycomb		1

Materials

Ethylene Vinyl Acetate (EVA)(Nanan Hongyang, 20kg/m ^{3}; 70% PE, 20% EVA, 7% foaming agent, 2% talcum, 1% colourant) was donated by Canterbury for use in Phase III. The foams were therefore compliant with the Body Padding Specification (World Rugby, 2019b) and comparative with current commercially available shoulder pads. Additionally, EVA was selected as the sole protective material in Phase III as the most popular used form of shoulder padding under study in Phase II. EVA was used at a thickness of 10mm, as that padding thickness was used for all nine garments in Phase II. Each laser cut pattern was fabricated in three samples of EVA foam.

Segmentation Method

The segmentation patterns were drawn using Adobe Illustrator CC (Adobe Systems Incorporated, USA). Body padding has been cut-segmented via methods such as laser cutting (Gordon et al., 2015) and die-cutting (Morrow and Winningham, 2006). However, laser cutting was the only readily available cut-segmentation resource to the researcher, enabling a cut quality similar to the standard of the Canterbury Raze Pro. A laser cutter (Lotus Laser Systems LL10060, 0.1 mm laser beam) was employed for the development of EVA with segmented by the five patterns. Additionally, computer aided manufacturing (CAM) provide more quality and control than by hand (Tharpe and Costin, 2019).

Garment and Shoulder Pad

Each shoulder pad was inserted into a top for assessment in Phase III. The Optimum Tribal Five Pad rugby top was chosen for insertion of the developed pads as the only rugby top accessed for Phase II featuring removable shoulder padding. Therefore, each of the developed pads could be inserted and switched by hand into the pre-made, commercially available rugby top. The shoulder pads were required to match the dimensions of the Optimum Tribal Five Pad shoulder padding so that they would fit inside each pocket as originally intended by the brand. Each shoulder pad had a 60.5 cm circumference, the same 8 figure shape with a narrowest middle width of 8.4 cm and widest top and bottom widths of 11.7 cm, shown in Figure 32.

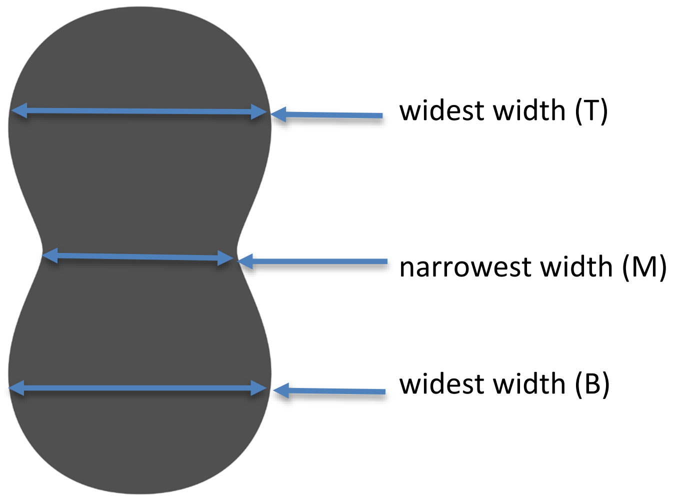


Figure 32: Shoulder pad with dimensions including T, M, B based on the Optimum Tribal Five Pad rugby top (Authors Own Image, 2017)

Tensile Displacement (Test 1)

Each of the five shoulder pads were subject to tensile displacement on a Testometric Micro 500 to confirm which samples were auxetic. Each sample was marked with three identical horizontal landmarks, T, M, B as shown in Figure 34, measured before and after tension. Each sample was subject to maximum extension in the vertical direction under tensile force in a 15 cm gauge, identified by audible or visible signs of the EVA foam breaking, three times for reliability. Tensile displacement was measured and timed by the Testometric Micro 500 but lateral displacement at T, M, B was measured by hand using a metal ruler. Internal structures that enabled lateral expansion under tensile displacement were determined auxetic and that which biaxially contracted was found not to be.

Tensile displacement also assessed the opening consistency of each segmentation pattern in relation to its porosity and lateral displacement. The percentage difference between the mean biaxial displacement of widest widths T, B and narrowest M were calculated and the results were compared. Of the five shoulder pads, that with a higher percentage difference showed less consistency and higher porosity at regions of highest axial strain. A greater difference in porosity at locations across the shoulder pads identified that regions of higher axial strain would have higher exposure to rugby impacts. Therefore, the ideal shoulder pad consistently opened out throughout the pad to minimise impact exposure at regions of highest axial strain. Tensile displacement tests were conducted on the same day within a lab with an expected room temperature of ± 20 °c.

Lateral Expansion of Pads Fitted to a Mannequin (Test 2)

Test 2 was designed to obtain the same lateral displacement data as test 1 but with the additional constraint of subjecting the shoulder pads to synclastic curvature. The five shoulder pads were separately inserted into the right-hand shoulder region of the Optimum Tribal Five Pad rugby top and fitted to a size XL Alvanon soft series mannequin (AVF 19921/40). The shoulder pads were curved over the shoulder region and embedded within a top stretched over the mannequin. Dimensional changes to the shoulder pads were assessed between fitting on a mannequin and in the original state on a flat surface. This method was conducted to demonstrate how shoulder curvature and extension of the stretch top affected the opening consistency and lateral expansion of pads featuring different auxetic segmentation patterns. The test was repeated three times for reliability and the mean was taken.

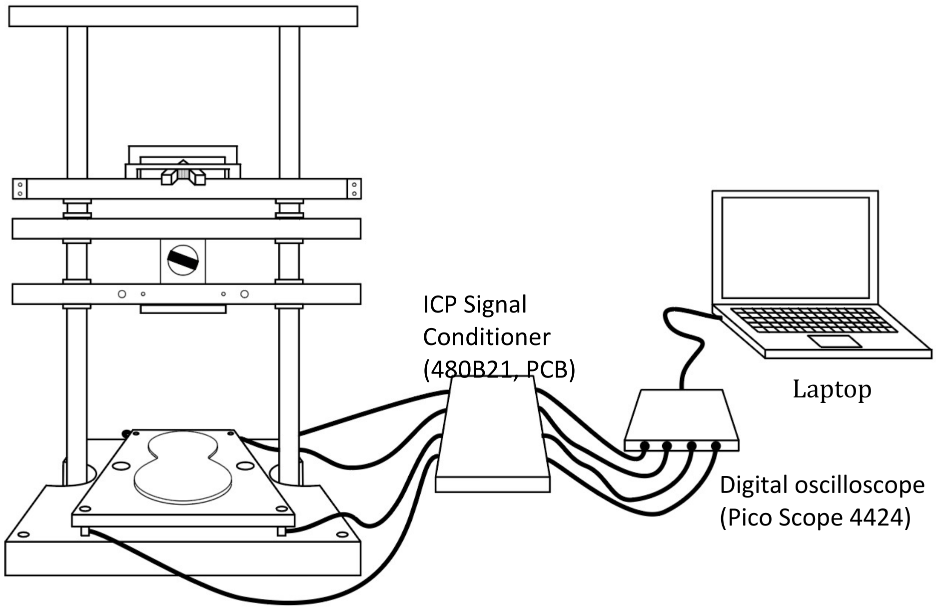
Pressure Comfort (Test 3)

Test 3 repeated the Phase II pressure comfort (mmHg) assessment method, as such a 50 mm diameter PicoPress sensor (PicoPress M-677, Microlab, Padova, Italy) was used. Measurements were obtained for the front and back shoulder landmarks over the four arm raises also justified for use in Phase II. Three measurements were taken at each landmark and the mean was calculated for reliability. The shoulder pads were embedded within the same top and fitted to the same mannequin as for test 2. The sensor was placed flat between the garment and the front and back shoulder landmarks by hand, as identified in Phase II, measurements were taken to the nearest 1mmHg.

Impact Tests (Test 4)

The five shoulder pads were subject to impact force attenuation tests over domed, cylindrical and flat anvils, as shown in Figure 33. Test 4 was performed using a bespoke drop tower rig, with a flat striker on two linear guide rails. The five shoulder pads were subject to a mass of 5 kg, impacted from a height of 10.2 cm. Four load cells (208C05-Force Sensor, PCB Piezotronics) were attached to the anvils with a sensitivity of 0.009109 m V/N, as detailed by the manufacturer). Thirty seconds was left between each impact, repeated three times for each pad, in accordance with the Body Padding Specification (World Rugby, 2019b).

a)



Four load cells (208C05-Force Sensor, PCB Piezotronics) attached to the anvil with a sensitivity of 0.009109 m V/N, as detailed by the manufacturer).

b) c)

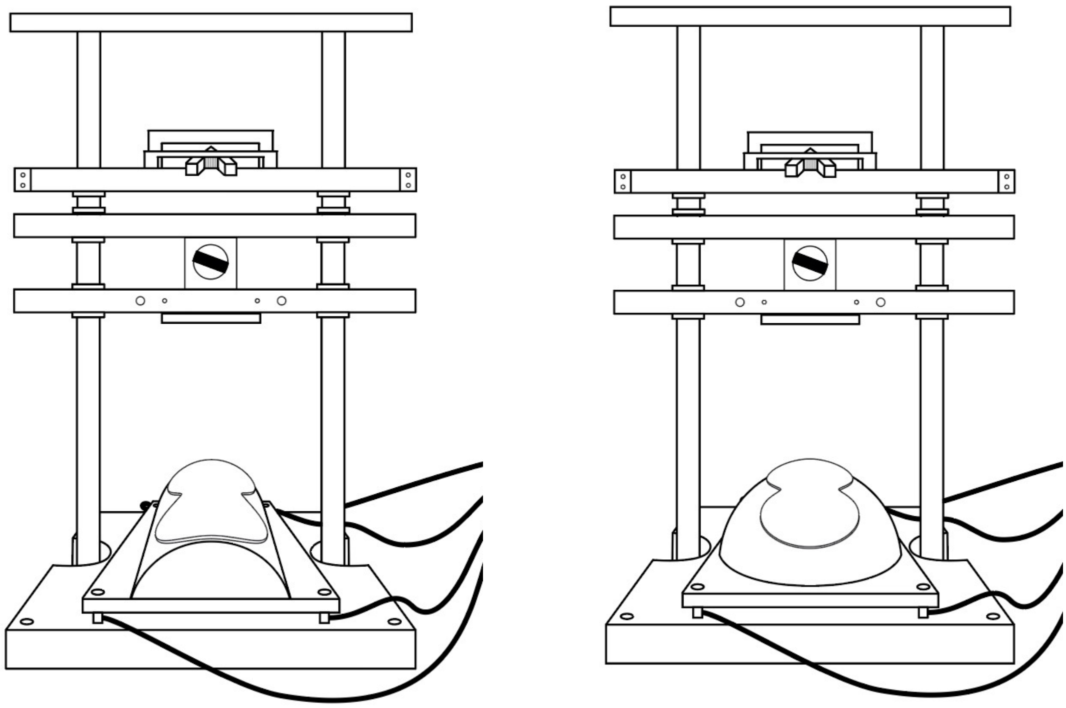


Figure 33: Bespoke impact rig made to the World Rugby Body Padding Specification (2019b), consisting of a domed striker, from a 10.2 cm height over a) flat, b) cylindrical and c) domed anvils (Authors Own Image, 2019)

3.4.2 Part 2 – Manipulation of One Auxetic Structure To Assess Suitability for Rugby Shoulder Padding

Part 2 of Phase III focused on the manipulation of one auxetic structure by tailoring its unit cell walls, known as ribs (Yang et al., 2004). The structure was identified as that which attenuated the lowest peak forces and greatest conformability across the four tests in stage 1. The ribs of the internal structures were manipulated by overall length, laser cut widths and anisotropy. Nine shoulder pads were developed and assessed in total, including eight manipulations plus the original structure. Identical materials and segmentation methods were used for part 1 and 2.

Cut Widths

In Phase II, it was identified that the dividing space (widths) between segments (unit cells) of the commercial rugby shoulder pads varied. The widths between the unit cells of commercial pads included 0.1, 0.2, 0.3 and 0.4 cm. Therefore, as laser cut-segmentation was used for Phase III, the space between each unit cell was defined as the cut widths between segments. The original sample developed in stage 1 featured cuts of 0.1 cm widths, the width of the laser beam, as such the manipulated versions featured increased cut widths. Only two variations from the original could be produced with manipulated cut widths, with the quantity of EVA foam provided, hence 0.25 cm and 0.4 cm were selected for development.

Rib Lengths

The length of each cell wall within the opened out auxetic structures were referred to as rib lengths, a term previously used for the same description regarding cells within auxetic foam (Yang et al., 2004). The rib lengths of the repeated unit cells that formed the segmentation patterns assessed in Phase II varied. The rib lengths reported for the Phase II rugby tops ranged from 0.5 cm to 1.5 cm. The stage 1 structures had rib lengths approximately 1.0 cm in length. Therefore, the manipulations explored the lower and upper bound of the range of nine commercial pads assessed in Phase II, 0.5 cm and 1.5 cm.

Anisotropy

All five segmentation patterns in stage 1 were comprised of the same length ribs. Anisotropic auxetic structures, which have more than one NPR value (Evans et al., 1994), have been found to achieve higher negative Poisson's ratio (NPR) than some isotropic (Yang et al., 2012), which have the same NPR value in all directions.

It was likely that one commercial rugby pad assessed in Phase II was also anisotropic, as its unit cells were comprised of varying rib lengths. Therefore, anisotropy was determined a suitable factor for exploration by manipulation. The rib lengths explored for anisotropy were 1.5 cm and 2.0 cm; vertical and horizontal ribs were manipulated separately, producing four samples in total.

3.5 Chapter Summary

The methodology and methods chapter has outlined the pragmatic research perspectives that underpinned the research strategy. The methodological framework has been designed to address objectives 1 – 4. Methods were formed for three Phases including a user perception survey (Phase I) and fit analysis of commercial rugby shoulder padding (Phase II) and development of auxetic shoulder padding (Phase III). The data collection and potential ethical implications of the research were described, and the findings are presented in the following chapter.

4 Results and Analysis (Phases I to III)

4.1 Introduction

Discomfort has been found to detract sports participants from wearing personal protective equipment (PPE) (Finch et al., 2001). Discomfort of sPPE can be attributed to its bulkiness, poor pressure comfort (Webster and Roberts, 2009) as well as restricting wearer movements (McQuerry et al., 2019). In contrast, auxetic structures have been broadly recommended for sport PPE, enabling synclastic curvature and greater conformability to curved surfaces (Liu and Hu, 2010). Sport PPE (sPPE) is available in sport and position specific variety, therefore this research had a product specific focus with the intention that its key findings would contribute to recommendations with possible implementation for rugby. Wearer discomfort has been commented on for rugby shoulder padding in the literature (Venkatraman and Tyler, 2016) but evidence based on user perceptions and garment analysis is limited.

Through a quantitative user perception survey, Phase I identified the user experience of rugby shoulder padding comfort (thermal, sensorial, aesthetic, protective, fit and weight). The survey sample comprised of male and female rugby Union participants', over the age of 18. In Phase II, six participants were fitted to nine commercially available rugby shoulder padded tops and pressure comfort was recorded from the front and back shoulder regions over four arm raises. The commercial rugby tops were categorised by shoulder pad segmentation type and fit was assessed in combination with pressure comfort. Phases I and II determined commercial rugby shoulder padding conformability and comfort; following this Phase III assessed how far geometric manipulations of auxetic structures could provide greater conformability compared to the current standard defined in Phases I and II.

Adequate conformability and fit of rugby padding proved difficult due to the curvature of the shoulder and its movement mechanisms. Previous investigations as to whether auxetic structures offer sPPE greater fit and conformability have neglected whether synclastic curvature affects impact protection. Therefore, Phase III was comprised of two parts; Part 1 identified the most suitable shoulder pad segmentation of five internal structures, including four auxetic and one non-auxetic for comparison. Physical tests included tensile, dimensional, pressure comfort and impact tests over one flat and two curved surfaces that imposed synclastic curvature. In Part 2, the internal structure that offered the greatest conformability, opening consistency and lowest peak forces was manipulated by scale to produce nine samples. The nine samples were subject to identical tests and validation from Part 1 providing enhanced knowledge of how sPPE cut-segmented with auxetic structures can enhance conformability.

This chapter presents the results from Phases I to III. The research problem was first investigated through the user (Phase I) and then the product (Phase II), to address the problem within the context of the current state of rugby shoulder padding. Findings from Phases I and II were critical to developing and accessing a possible alternative to current rugby shoulder padding (Phase III). This chapter reports the quantitative analyses and an overview of the key findings obtained for each phase. The chapter fulfils objective 2 (Phases I and II) and objectives 3 – 4 (Phase III).

4.2 Phase I - User Perception Survey of Commercially Available Shoulder Padded Rugby Tops

This section reports data obtained from the rugby shoulder padding user perception survey, shown in Appendix A. Current research of rugby shoulder padding has a focus on impact protection (Harris and Spears, 2010), largely neglecting user perceptions of comfort (Webster and Roberts, 2009). The survey identified the distribution of participants that wore shoulder padding and its criticality to their perceived safety during rugby participation. Phase I determined how far the six realms of comfort; aesthetic, protection, sensorial, fit, thermal and weight (Webster and Roberts, 2009) influenced the participants' wear and purchase of rugby shoulder padding. The survey was distributed over a period of three months and completed by a total of 139-rugby Union participants. The results are presented thematically by participants background, product use, injury, behaviour and attitude.

4.2.1 Participants Background

Of the 139 participants, males aged 25 - 34 years old were the highest represented group, as seen in Figure 34. The gender distribution was consistently skewed towards men across all three-age categories and the groups were not continuous. Of the 7.23 million rugby Union players in 2014, only 1.76 million were female (Jacobs and Sellars, 2019). 2.7 million women were found to participate in rugby Union in 2019 (BBC Sport, 2019), yet they remain a smaller percentage of rugby players. The survey reached 30% female respondents in its distribution compared to 70% male – over double the female sample, therefore the sample reflected the gender population.

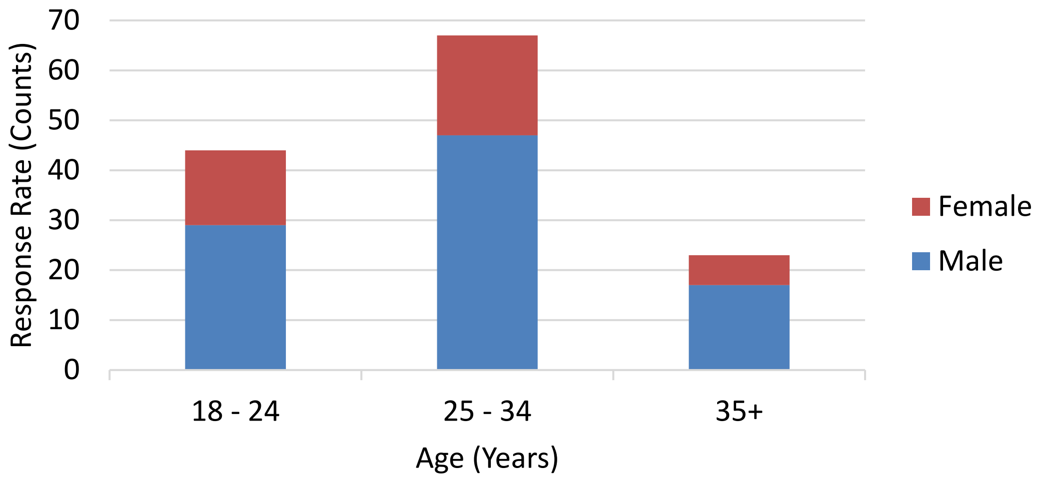


Figure 34: Respondents age by gender

Of the respondents, 21% played positions that exposed them to the least number of tackles, 38% played roles that left them exposed to a medium number of tackles and 42% of respondents were exposed to the highest number of tackles. Therefore, the responses remained uneven after re-coding, such that the majority of respondents played Flanker, 2nd row and Number 8 positions. Respondents were also asked to categorise their training levels and Figure 35 shows that 67% of the respondents played at a competitive level, for example organised rugby Union through a University. The results also indicated a lower representation of professional (club level participation) and recreational training levels (participation organised locally with no authoritative management).

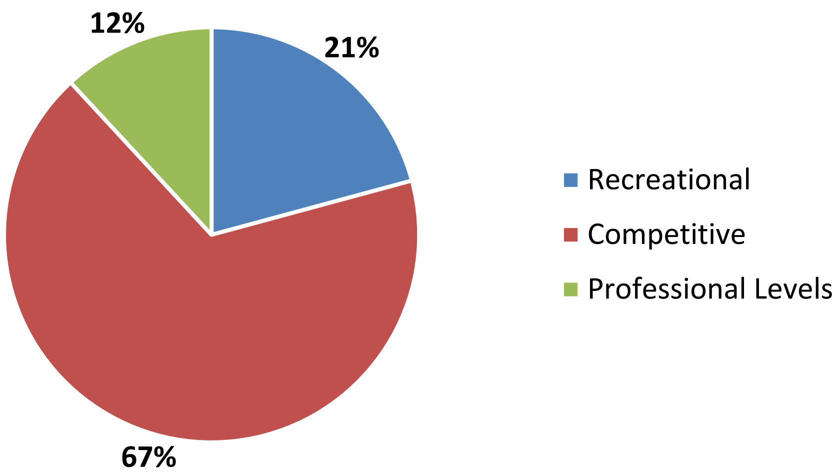


Figure 35: Respondents training levels

4.2.2 Statistical Analysis of the User Perception Survey

Statistical and key findings were analysed per survey theme: product use, injury, behaviour and attitude. Statistical analysis determined relationships between the independent and dependent variables. Parametric assumptions were identified using Levene's test and normality Q-Q plots, which were reported in Appendix B. The parametric assumptions enabled the identification of the correct bivariate analysis tests to run per variable. Where parametric assumptions were acheived, a T-test or Kruskal-Wallis test was performed, where they were not a Mann-

Whitney test for significance was performed, full data sets can be found in Appendix C. Respondents were given the option to choose ‘prefer not to say’, these responses were excluded from the analysis presented in this section.

4.2.2.1 Rugby Shoulder Padding Product Use

In this section of the user perception survey, respondents reported the frequency of wearing rugby shoulder padding. The response option ‘never’ was answered by participants that had never worn rugby shoulder padding before. The remaining response options showed varying frequencies to which participants wore rugby shoulder padding. Figure 36 presents the frequency of shoulder padding wear.

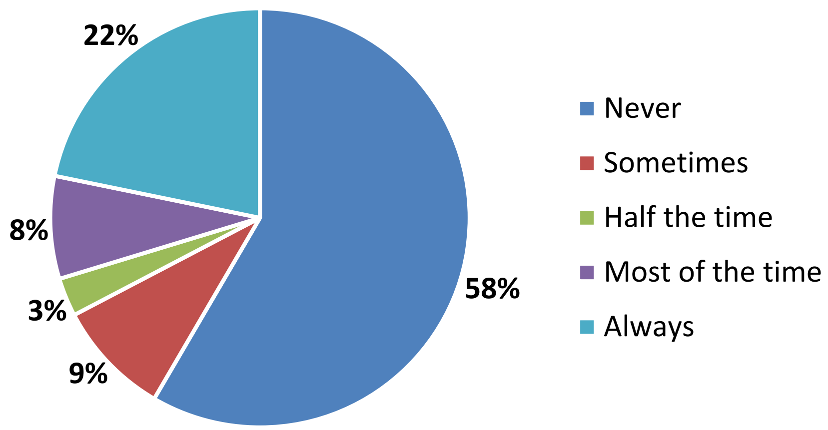


Figure 36: Shoulder padding wear

No significance ($p > 0.05$) was identified between age, training level, position or gender and the choice to wear shoulder padding. Two thirds of respondents never wore shoulder padding, whereas sometimes, half or most of the time accounted for two fifths of respondents and a fifth always wore rugby shoulder padding. It was striking that two thirds of participants, did not wear shoulder padding. In 2001, Finch et al., (2001) identified that fewer than 40% of a sample of rugby players wore shoulder pads. Therefore, the finding that two thirds of the sample did not wear rugby shoulder padding implies that product use was similar to that identified by Finch et al., (2001) twenty years ago.

4.2.2.2 Injury

Respondents were asked to score how they perceived rugby shoulder padding had helped to protect them against injury. Participants that did not wear rugby shoulder padding had the option to choose not applicable and their answers were excluded from the results for this section. Injury was categorised as four types; minor injuries including soft tissue damage and lacerations as well as major injuries, dislocation and breakage. Figure 37 presents the results as percentages.

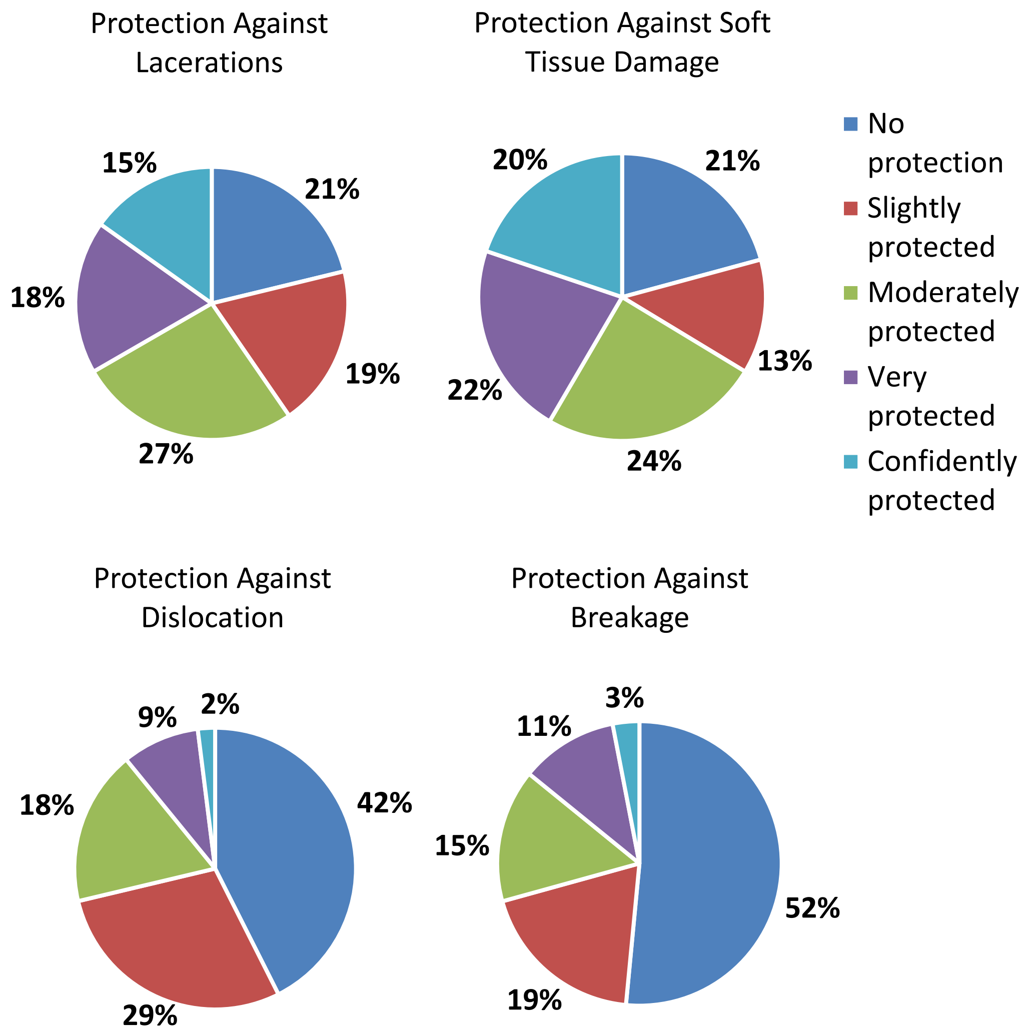


Figure 37: Belief in the protectiveness of shoulder padding against injury

Rugby shoulder padding is designed to protect against minor injuries that include soft tissue damage, cuts and lacerations, as they can bottom out under the high impacts that cause severe injuries (Harris and Spears, 2010). Therefore, it was interesting that approximately half the respondents believed shoulder padding protected them against severe injuries like dislocation and breakage. However, a higher majority of participants believed that rugby shoulder padding protected against minor injuries than major injuries. Figure 39 shows that over 14% of participants felt protected against lacerations and soft tissue damage, whereas less than 4% felt confidently protected against dislocation and breakage. In addition, over 41% of respondents perceived that rugby shoulder padding offered them no protection against major injuries, compared to 21% that felt it offered no protection against minor injuries. No significance ($p > 0.05$) was identified between age, training level, position or gender and participants beliefs in the protectiveness of PPE.

4.2.2.3 Behaviour

This section of the survey identified peer and comfort to influence participants choice to wear rugby shoulder padding. Survey respondents reported the perceived effect of rugby shoulder padding across six realms of comfort during rugby participation. Responses were also recorded for how far family, teammates and coaches influenced their choice to wear rugby shoulder padding. For each realm of comfort respondents were given the option to choose not applicable and these answers were excluded from the results presented in Figure 38.

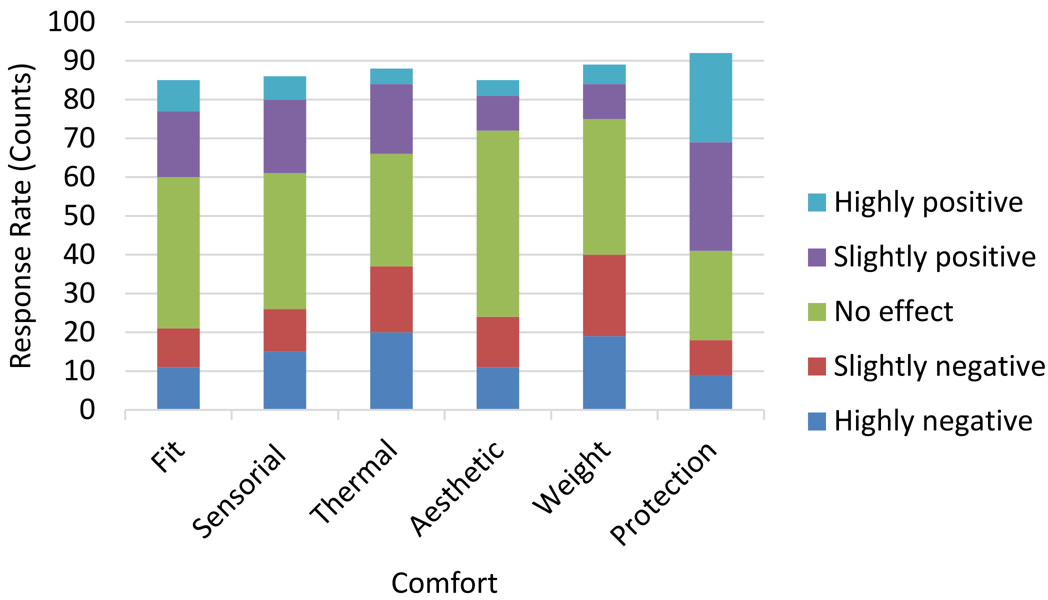


Figure 38: Responses for the effect shoulder padding had on the six realms of comfort during a match

No significance ($p < 0.05$) was identified between the age, training level, position or gender of the respondents and their comfort during rugby participation whilst wearing shoulder padding. Figure 38 showed that protection and fit were the most satisfactory realms of comfort through shoulder padding wear, yet only 29% felt strongly that rugby shoulder padding provided fit comfort. Beliefs that wearing rugby PPE can increase injury risk (Malcolm et al., 2005) are still prevalent, as 20% of respondents felt strongly that rugby shoulder padding hindered their protective comfort. User satisfaction was low for all six realms of comfort including sensorial and thermal but the strongest negative association with comfort were the respondents perceived weight comfort. Almost half of the respondents felt strongly that shoulder padding had a negative effect on their perceived weight comfort; this realm of comfort has posed a challenge across the design of other sport PPE (Abdelmalek, 2019; Schneider et al., 2019; Tong, 2019) including helmets (Stolker, 2018).

Figure 39 shows that the majority of respondents felt their decision to wear or not wear rugby shoulder padding had not been influenced by family (61%), teammates (58%) or coaches (73%). However, family was the only group that respondents felt had encouraged (30%) more than they had discouraged (9%) them from wearing PPE. In particular, a statistically significant difference of $p = .02$ was identified, showing that the 18 – 24 years group were more encouraged to wear PPE based on influence from their family members than those over 35 years. Carter (2015) argued that children are more physically vulnerable to rugby injury. Therefore, as the youngest of the three age groups it was not surprising that the 18 – 24 age group received more encouragement to use injury reduction measures by their family.

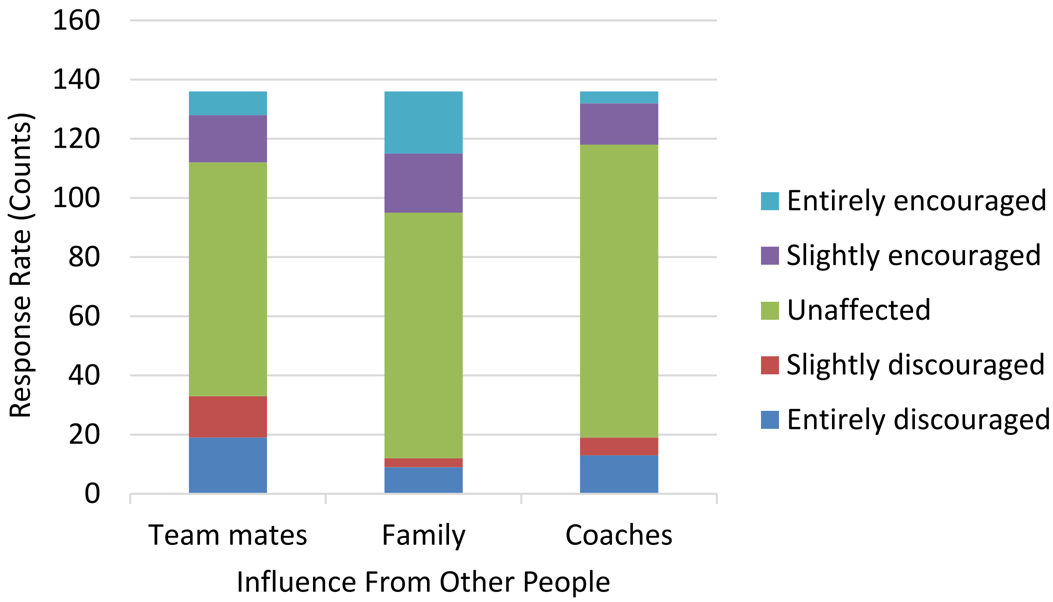


Figure 39: Responses for how far the wear of shoulder padding was influenced by teammates, family and coaches

A statistically significant difference of p= .03 was found between the training levels of respondents and how far discouragement from teammates had affected their choice to wear PPE. Further post hoc analysis of p = .02 revealed that professional participants had received greater discouragement from their teammates than competitive level respondents. Injury management varies between playing levels (World Rugby, 2019a) where those playing at professional levels had greater access to resources such as team doctors present at matches. As such, it is arguable that without the same level of injury management, non-professional rugby players may have more appreciation for accessible injury reduction measures, such as PPE. However, teammate discouragement from wearing rugby shoulder padding suggests that within the sport, the wear of PPE may be believed to cause more injuries than it prevents (Low, 2015).

4.2.2.4 Attitude

Respondents’ attitude to wearing rugby shoulder padding were assessed. Figure 40 displays opinions of whether rugby shoulder padding met respondents’ needs across the six realms of comfort. Respondents were given the option to select not applicable; the highest number of responses were received for fit comfort. Figure 40 displays respondents' rank positions for how critical the six realms of comfort would be to them in purchasing rugby shoulder padding.

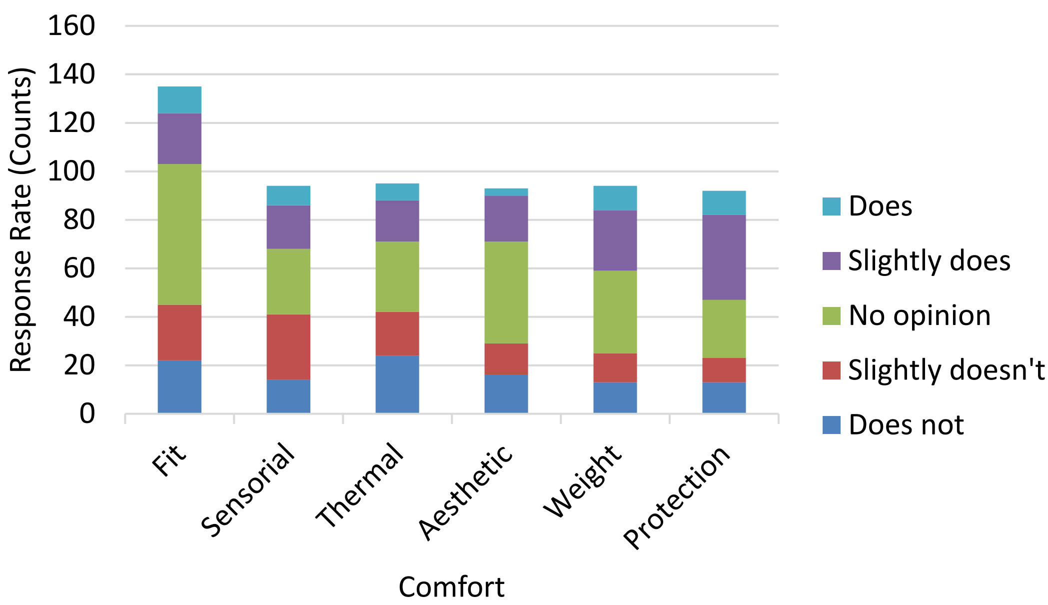


Figure 40: Responses for how far shoulder padding met comfort requirements

Respondents that did not wear rugby shoulder padding were able to choose the Not Applicable (N/A) option when it was a requirement for answering that question. Figure 40 showed that fit gained approximately 50% more responses than the remaining five comfort realms in whether shoulder padding met rugby participants' comfort requirements. A third of respondents selected N/A for the remaining five realms of comfort, rather than skipping the questions which implied that they were not subject to survey fatigue (Story et al., 2019). The observed higher counts for fit suggested that it was more critical to their comfort. Therefore, it was identified that fit played the most memorable part in the wearer's experience of garment comfort.

Figure 40 shows that perceived protection was found to meet respondent requirements more so than any other realm of comfort; 'slightly does' was the most popular answer for protection. In contrast, shoulder padding was not found to meet respondents' aesthetic comfort requirements. The responses showed that recreational level players felt that rugby shoulder padding provided significantly poorer aesthetic comfort than competitive level respondents, which was $p = .03$. Significance $p < .01$ was also identified for gender and fit comfort; shoulder padding slightly met the fit requirements of men but it slightly did not meet female respondents' comfort requirements. Shoulder padded rugby tops can be bought as gendered garments to prevent breast injuries (Brisbine et al., 2019), fit comfort can be worse as the closed cell foam is typically of a larger surface area that covers the bust.

Respondents were asked to rank the six realms of comfort in order of influence on their shoulder padding purchasing decision; no significance ($p > 0.05$) was identified with respondent backgrounds. Respondents were least likely to compromise on protection and fit comfort when purchasing rugby shoulder padding, as seen in Figure 41. This finding was interesting given that protection slightly met respondents' comfort requirements and fit most popularly slightly met the requirements of male participants. Therefore, respondents were more likely to compromise on the realms of comfort that were not found to meet their weight, thermal, aesthetic and sensorial comfort requirements. However, given that fit and protection were most critical to respondents' purchasing decision and only a third of respondents wore shoulder padding, a more satisfactory experience of protection and fit may have encouraged wear.

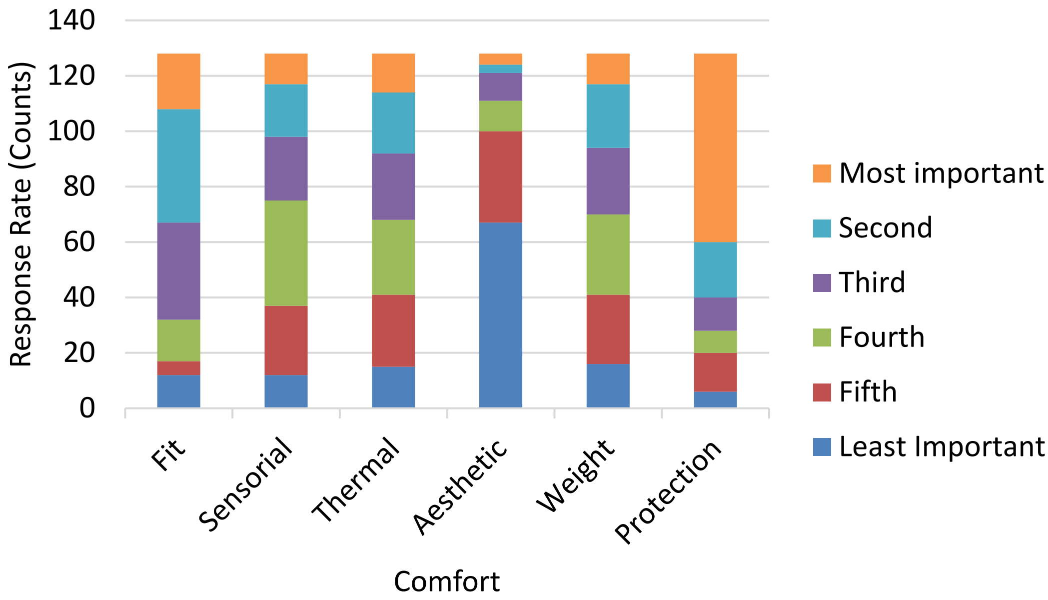


Figure 41: Responses for the rank order of importance of the six realms of comfort to the shoulder padding purchasing decision

4.2.3 Summary of the User Perception Survey

Survey respondent shoulder padding use was similar but 7% lower than research from 2001 (Finch et al., 2001), despite an increase in the rate of rugby injury since that time (Montgomery et al., 2018; World Rugby, 2018). 80% of the respondents believed in the protective capabilities of shoulder padding against the minor injuries it was designed for. Over half the respondents thought that shoulder padding was able to protect them against dislocation and breakage. Therefore, more survey respondents believed in the intended protective capabilities of shoulder padding than those that wore shoulder padding, suggesting there are other reasons that have detracted players from wearing PPE. Instead discouragement from rugby teammates and coaches contributed to the low popularity of shoulder padding wear and more so for respondents that played at professional levels.

Despite beliefs in the protective capabilities of rugby shoulder padding, the overall perceptions of its comfort were poor across the six realms. Discomfort is considered the primary reason for not wearing sPPE (Kajtaz and Subic, 2019) and the findings suggest that discomfort may have been a leading factor for shoulder padding unpopularity in the sample. It was identified that protection and fit were the most critical comfort factors to the respondents' decision to purchase rugby shoulder padding. This finding was unsurprising as fit is critical to proper positioning of PPE (Cubeddu, 2016) and protection is its purpose. Fit and protection were the most satisfactory realms of comfort, yet they only 'slightly' met respondents' comfort requirements and fit comfort was reported as unsatisfactory for female respondents.

Weight, thermal, sensorial and aesthetic comfort were found to cause discomfort during rugby participation and did not meet the requirements of the respondents. Previous research has described non-stretch rugby shoulder padding, embedded within a streamline stretch sports top, as bulky (Tyler and Venkatraman, 2012); the closed cell foams are non-breathable and can trap air (Wyner et al., 2017), providing poor thermal comfort. The findings from this study confirmed that the bulky appearance of shoulder padding was detrimental to respondents' perceived aesthetic comfort. Bulkiness of shoulder padding also increases the sensation of weight and a difference in stretch between the padded region and non-padded regions leads to poor pressure comfort which can be experienced sensorially (Sweeney and Branson, 1990). Therefore, findings from the study suggested that the bulkiness, non-breathable and non-stretch of current shoulder padding led to poor comfort, which may have resulted in the low percentage of respondents that wore rugby shoulder padding.

The findings from the survey confirmed that user discomfort had a detrimental effect on the wear of rugby shoulder padding. Due to the ability for auxetic structures to open out and expand, these structures offer the potential to enhance the breathability of PPE (Sanami et al., 2014b), and improve thermal comfort. The ability for auxetic structures to expand (Sanami et al., 2014a) laterally under tension (Martin, 2011; Cross et al., 2015) could enable conformability to stretch fabrics, in turn improving perceived sensorial and weight comfort. The synclastic curvature of auxetic structures (Lakes, 1987; Wang and Hu, 2014) also has potential to improve the fit of rugby shoulder padding by conforming better to that curved body region. The fit and comfort of particular shoulder pad types must be determined in order to assess whether auxetic structures have potential to enhance the comfort of PPE.

Summary of Key Findings

Phase I established that 58% of the sample do not wear shoulder padding compared to the 22% that always wore them. It was established that rugby shoulder padding is not critical to the majority of respondent perceptions of safety and protection during rugby participation. Additionally, a higher majority believed in the protective capabilities of padding against minor injuries than major injuries. The survey also established that respondents wear rugby shoulder padding due to influence from family members, in particular younger participants are more likely to feel encouraged to do so. However, respondents may not wear rugby shoulder padding due to influence from their teammates and coaches; professional level players reported greater discouragement. The survey determined that the level of fit and protection provided by rugby shoulder padding were the most important realms of comfort to respondents.

4.3 Phase II

4.3.1 Pilot Study: Characterisation of Rugby Shoulder Padded Tops

The findings from the pilot study are found in appendix D. The fit pictures showed that Gilbert and Canterbury garments were more suited to the participant's size, whereas the Optimum and Kooga tops both appeared much tighter throughout the garments. The measurement charts confirmed that the Optimum and Kooga tops had narrower chests compared with the other XL garments. Fit analysis of one participant was deemed suitable for this study as the investigation focused on differences between pads. However, It was established that a greater range of size XL body types were required to confirm which rugby top had the most conforming, best fitting shoulder pads. Therefore, the choice to use one participant for the fit assessment was considered a limitation of the pilot.

The fit analysis established issues common to all of the shoulder padded tops, as shown in appendix D. In particular, none of the pads were found to conform fully to the curved shoulder region. Although some segmentation types led to greater conformability than others. In addition, the ways in which the shoulder pads failed to conform fully were dependent on segmentation type. Figure 42 presents the fit and conformability of each of the five rugby tops to the participant's right shoulder region.

a) Canterbury Vapodri Raze
b) Canterbury Vapodri Raze Pro
c) Gilbert Triflex XP1
d) Kooga IPS V
e) Optimum Tribal Five Pad

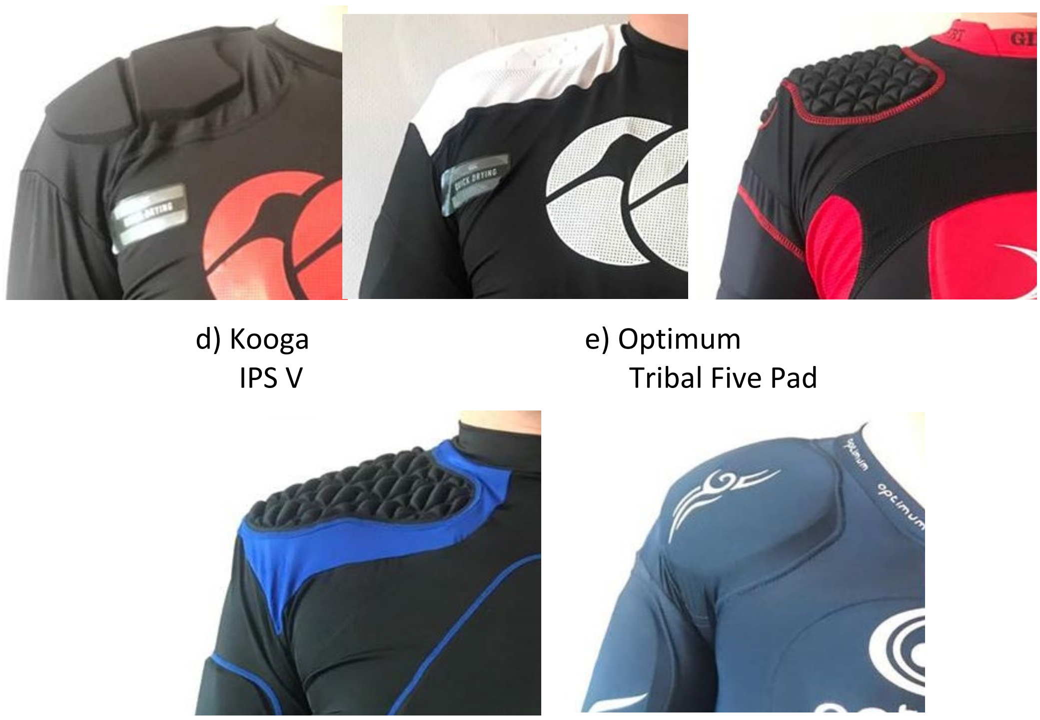


Figure 42: Front view of each righthand shoulder pad fitted to the participant (Authors Own Image, 2017)

In Figure 42e, towards the participant's neck the unsegmented shoulder pad appeared raised away from the body. Figure 42a displayed the same fit problem for the quartered and individually pocketed padding. Although the Canterbury Vapodri Raze (Figure 42a) padding was quartered to improve conformability, the four pieces of foam on either shoulder were not subject to further segmentation. In addition, the padding of the Canterbury Vapodri Raze was of a smaller circumference than the Optimum Tribal Five Pad, which would have enabled it to conform better. Therefore, the Canterbury Vapdori Raze shoulder padding could have been considered partially unsegmented and it showed similarity to the entirely unsegmented Optimum rugby top.

Vacuum moulded shoulder pads enabled greater fit than the unsegmented alternative yet were also problematic. In both figure 42c and 42d, the vacuum moulded pads pulled away from the shoulder. At the upper arm, where the vacuum moulded shoulder pads pulled away from the shoulder there was noticeable pulling of the surrounding fabric, as seen in Figure 43. Whereas, when the participant's arms were raised, the pads sat flat against that region of the shoulder. Therefore, it was evident that the vacuum moulded shoulder pads were able to move position during wear, showing poor conformability.

a) Gilbert Triflex XP1 b) Kooga IPS V

Figure 43: Lefthand side view of the vacuum moulded shoulder pads fitted to the participant (Authors Own Image, 2017)

The rugby shoulder padded top with the best observed fit was the cut-segmented Canterbury Vapodri Raze Pro. In figure 42b, the cut-segmented top appeared to conform well to the curvature of the shoulder region. However, the fabric that the padding was embedded within bunches at the padding circumference and does not sit flat. Both Canterbury garments appeared to have excess fabric that bunched surrounding the shoulder padding, although the garments were otherwise taught across the fit model's chest and body. Loose fitting shoulder pads could lead to improper positioning on the body (Cubeddu, 2016) particularly during body movement.

Key Findings

The pilot obtained findings from one body type; Phase II developed on this to compare multiple participants of a range of XL body shapes. The study also benefited from a variety of shoulder padded garments within each segmentation type, in order to identify similarities in the segmentation type characteristics. In addition, the technical specification data provided some use for understanding the garment fit but it did not reveal the effect of poor fitting shoulder padding. Therefore, pressure comfort analysis was utilised instead in Phase II as a known route to quantifying the effect of garment fit on the body. The literature review identified that researchers have used pressure comfort analysis to determine changing pressure levels produced between clothes and body landmarks during movement.

The pilot of Phase II profiled the fit issues common to different types of shoulder pad segmentation and those common to all three segmentation types. All pad types were found to splay away from the shoulder but this was most problematic for unsegmented pads. In contrast, segment bunching was identified exclusively for vacuum moulded pads. It was significant that segmentation types influenced particular fit patterns despite differences in pad positioning on the shoulder and overall garment fit. Therefore, it was identified that enhancing padding conformability could be investigated through segmentation.

The research has a focus on the conformability of padding rather than the overall garment technology. As such, the garment specifications were excluded from Phase II. However, the garment specifications showed that padded tops comprised of different joining technologies, construction methods and dimensional differences. The differences in garment technology all contributed to the overall fit of the garment. Investigations into garment technology will be critical in wider research of sPPE with enhanced fit and may incorporate the findings of this research regarding padding segmentation.

4.3.2 Fit Analysis of Current Rugby Shoulder Padding

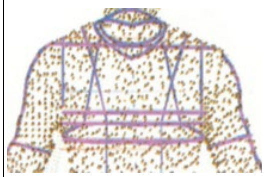
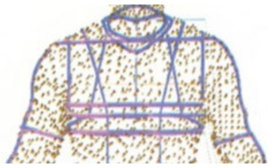
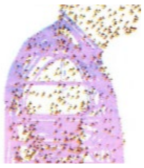
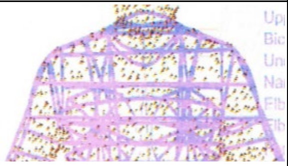
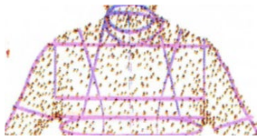
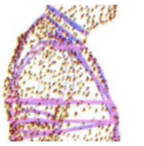
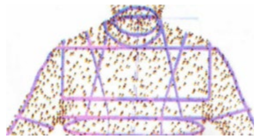
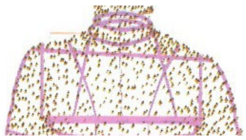
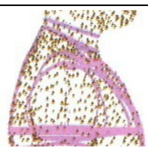
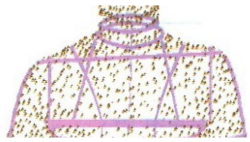
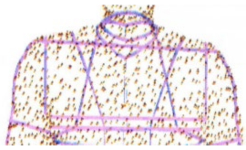
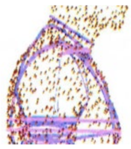
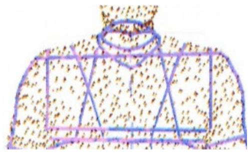
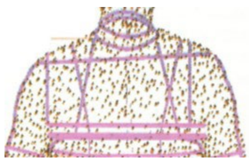
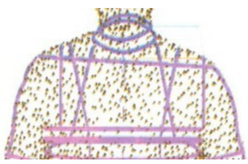
Rugby shoulder pads have been subject to impact tests, as an established method of assessing performance (Beer and Bhatia, 2009), neglecting user comfort. Other sPPE has been found to cause wearer discomfort (McIntosh and McRory, 2001; Gentry, 2018; Rome, 2019). Rugby tasks are also associated with dynamic and athletic movements encompassing a range of shoulder mechanisms (World Rugby, 2014). As such, rugby shoulder pads should generate good, consistent pressure comfort during body movements (Senthilkumar et al., 2012), although a range has not yet been defined. In Phase I, rugby shoulder padding led to perceived discomfort, associated with its bulkiness and restrictiveness, which can be experienced through pressure comfort (Webster and Roberts, 2009).

Phase II assessed the pressure comfort and fit of nine rugby shoulder padded tops, by recording a front and back measurement at four arm raises. The shoulder pads were categorised as non-segmented, laser cut and vacuum moulded and analysed per segmentation type. The optimum pressure comfort values for shoulder padding are not defined, therefore a fit assessment was conducted. Fit assessments identified conformability to the shoulder region, including puckering and splaying of the padding, in which it lifts away from the body. Body scan data for each of the six participants was obtained to determine their suitability to the garments, affecting fit and pressure comfort.

4.3.3 Fit Assessment Participants

Table 7 shows the chest circumferences of the six participants obtained from body scan data and the corresponding upper body maps. The chest circumferences were within the range identified for the nine XL rugby tops, 107 – 115 cm. Participants 4 – 6 chest circumferences were approximately 115 cm, the upper limit of the range identified for Phase II. Whereas, the chest circumference of participant 2 was approximately 107 cm, the lower limit. The chest circumferences of participants 1 and 3 were 109 cm and 112 cm respectively, the middle of the range. Therefore, participants 1 and 3 were expected to find the most suitable fit across the tops but all participants were deemed suitable for the study.

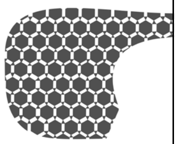
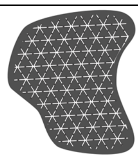
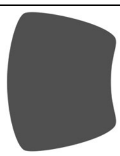
Table 7: Participant chest circumferences and upper body scan maps

Participant	Chest (cm)	Upper Body Region		
		Front	Side	Back
1	109.28			
2	107.42			
3	112.28			
4	114.80			
5	114.53			
6	114.96			

4.3.4 Garment Analysis

Each of the nine rugby shoulder padded tops was selected in a size XL but the respective shoulder pads differed in scale and shape. Table 8 presents the technical drawings for the nine shoulder pads and the respective segmentation types. Dimensional differences between the nine shoulder pads were also documented in Table 8. The smallest shoulder pad circumference was identified for garment A, whereas, garment D had the largest. The shoulder pad with the largest segmentation space between unit cells was garment B and the smallest was recorded for garment H, an unsegmented pad.

Table 8: The nine shoulder pads

	Top	Technical Drawing (Not To Scale or proportions)	Shoulder Line (cm)	Over Shoulder (cm)	Circumference (cm)	Between Segments (cm)	Number of Sides per Segmentation Unit Cell (cm)
A	Canterbury Vapodri Raze		14.5	18.0	59.5	0.3	N/A
B	Canterbury Vapodri Raze Pro		14.2	18.1	70.3 (half)	0.4	Hexagonal: 1 x 1 x 1 x 1 x 1 x 1
C	Gilbert Triflex Match V3		17.8	24.9	75.4	0.1	Triangular: 3 x 3 x 3
D	Gilbert Chieftain V3		17.5	23.2	76.9	0.3	Triangular: 2 x 2 x 2
E	Gilbert Atomic Zenon		10.8	23.0	70.4	0.2	Hexagonal: 2 x 2 x 2 x 2 x 2 x 2
F	Gilbert Triflex XP1		15.7	23.0	76.0	0.1	Triangular: 1.8 x 1.8 x 1.8
G	Kooga IPS V		17.0	22.0	72.0	0.2	Rectangular: 3 x 1.4 x 2 x 1.2 Triangular: 1.6 x 1.6 x 2.4
H	Body Armour Tech Vest BA		16.5	24.3	72.3	N/A	N/A
I	Body Armour Flexitop BA		15.1	26.2	82.1	0.1	Hexagonal: 1 x 1 x 1 x 1 x 1 x 1

4.3.5 Garment Fit

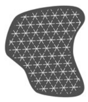
The six participants were photographed from a front and back position in each of the nine garments. Fit evaluations for each top were based on observations of the conformability of the shoulder pads to the shoulder region. Indicators of poor conformability were determined by observed puckering and splaying of the fabric or protective material, identified largely across the vacuum moulded shoulder pads. Garments H and D were found to splay the most, the former was unsegmented and the latter had the largest pad circumference and was considered bulky. The garment fit assessments can be found in Appendix E.

The narrowest chest circumferences were recorded for Body Armour garments H and I. Garments H and I had the worst fit on the participants exhibited by fabric pulling where it surrounded the shoulder padding, indicating that it was too tight. Therefore, it was unsurprising that garments H and I had the best fit on participants 1 and 2, as they had the smallest chest circumference. In contrast, garment E had the loosest fit across the six participants, it appeared oversized and loose fitting even for the broadest participants 4, 5 and 6. The ideal fit was identified as that which sat close and flat against the shoulder region, with adjoining fabric taught against the body; Canterbury garments A and B provided the best fit.

4.3.6 Pressure Comfort Measurements of the Shoulder Pads

Three repeated measurements were taken using the pressure comfort sensor from a front and back shoulder landmark of the six participants in each of the nine tops, over four arm raises. Body surface differences between participants have been found to affect pressure comfort accuracy (Chassagne et al., 2016; Thomas, 2014), therefore the mean was calculated from the three repeated measurements for reliability. An inability to control the movement variance of each top between tests also influenced the decision to calculate the mean. Table 9 displays the mean pressure comfort measurements obtained for Phase II, the full set of results can be found in Appendix E.

Table 9: Mean pressure comfort measurements (mmHg) for participants 1 – 6

Tops	Positions	Front						Back					
		1	2	3	4	5	6	1	2	3	4	5	6
A 	Stationary	5.0	1.3	1.0	0.3	1.0	0.7	4.0	1.7	4.3	2.0	7.3	1.7
	Mid raise	2.0	3.0	0	0.7	1.0	0	1.0	1.7	3.0	2.3	2.0	1.0
	45 degrees	1.3	1.0	1.7	2.7	6.3	0	1.0	1.0	0.7	1.0	1.0	0
	Overhead	1.3	5.3	1.0	2.7	7.0	2.0	1.0	0	0	0.7	1.0	0
B 	Stationary	5.7	1.0	3.3	2.7	6.3	2.7	3.3	3.3	3.0	3.7	5.3	1.7
	Mid raise	1.3	0.7	0	1.0	0	0	0	1.0	1.0	2.0	2.0	3.7
	45 degrees	0.3	0.7	0	0	2.3	0	0.3	0.7	0	1.0	2.0	1.0
	Overhead	3.7	2.7	0.7	0	4.7	0.3	0	0	0	0	1.0	0
C 	Stationary	4.3	0.7	2.0	0	0	3.7	1.3	1.7	1.7	1.0	7.3	2.3
	Mid raise	2.7	0.7	0	0	5.7	0	0	0	1.0	4.7	1.0	1.7
	45 degrees	0.7	0	0.7	0	1.0	0	0	1.0	0.7	1.0	5.0	0
	Overhead	1.3	2.3	7.7	0	0	0	1.0	1.0	0	1.0	4.0	0.7
D 	Stationary	8.3	0	0.7	0	2.0	0	0.7	0	0	1.0	3.0	1.3
	Mid raise	0.3	0	0	0.7	0	0	0.3	0	1.7	1.0	4.7	1.7
	45 degrees	0	0	0	1.0	0	0	0	0.7	0	0.7	2.0	0
	Overhead	0.7	0	2.7	1.3	0	0	0	0	0	0	0	0
E 	Stationary	0.3	0	0.7	0	0	6.7	1.3	1.0	0.7	0.7	3.0	1.0
	Mid raise	0.3	0.7	0.7	0.7	4.7	0.3	0	0	0.7	2.3	1.0	0.7
	45 degrees	0	0	0	1.0	3.0	0.3	0	0.7	0	0	1.0	0.7
	Overhead	0	0	0.7	2.0	1.0	0	0	0	0	0	1.0	0
F 	Stationary	4.3	0	0.7	1.0	0	2.3	0.7	0	0.7	1.0	5.7	0
	Mid raise	3.7	1.0	0	0.7	3.0	0.3	0.7	0	1.0	3.0	1.0	1.0
	45 degrees	0	1.0	1.0	1.0	3.7	0	0.7	0	0	0	1.0	0
	Overhead	2.7	3.3	1.0	2.0	1.0	0.3	0.3	0	0	0	0	0
G 	Stationary	3.7	1.3	1.0	0	2.0	0.3	1	0.7	2	1.7	6.7	3
	Mid raise	1.3	0.7	0	0	0	0	0	0	0.7	3	3	2.7
	45 degrees	1.0	0	0	4.3	2.0	0	1	0	0	1.3	2	0
	Overhead	1.3	0.7	1.7	11.0	4.7	0	0	0	0	0	0	0
H 	Stationary	3.0	1.0	0	0	0	0	3.7	1.0	2.0	1.0	3.7	4.3
	Mid raise	0.7	0	0	0	0	0	0	0	1.0	1.7	2.0	3.7
	45 degrees	0.3	0	0	0	3.0	0	0	1.0	0	0	0	0
	Overhead	6.3	4.3	0	0	2.0	1.0	0	0	0	0	0	0
I 	Stationary	0	0.7	0	0	0	0	4.0	1.0	2.0	1.7	5.7	2.7
	Mid raise	0	0.7	0	0	0	0	0.7	0	0.7	2.7	5.0	2.7
	45 degrees	0	0	0	0	0	0	4.0	0	0	1.0	2.0	1.0
	Overhead	1.0	0	0	0	0	0	0	0	0	0	0	0

* 0 mmHg = No Contact

* a) Canterbury Vapodri Raze, b) Canterbury Vapodri Raze Pro, c) Gilbert Triflex Match V3, d) Gilbert Chieftain V3, e) Gilbert Atomic Zenon, f) Gilbert Triflex XP1, g) Kooga IPS V, h) Body Armour Tech Vest BA, i) Body Armour Flexitop BA

An ideal pressure comfort range was defined as > 0 mmHg and < 3.2 mmHg, based on current knowledge of medical (Lymed, 2018) and sports compression wear (Brubacher et al., 2017). Stretch enables medical and sports compression garments to transfer benefits to the wearer but rugby shoulder pads are without stretch. Therefore, medical and sports compression grade pressure values were deemed to be outside of the ideal range for this research, including measurements above 3.2 mmHg. Finally, '0 mmHg' pressure indicated that the shoulder pad was not in contact with the shoulder and was a bad fit, hence 0 mmHg was defined as lower than the ideal range. Table 9 shows that Canterbury garment A fitted to participant 4 recorded values between 0.3 – 2.7 mmHg, indicating that it was the only garment that provided the ideal pressure comfort range, which is analysed in the following section.

4.3.7 Pressure Comfort and Fit Analysis

Patterns in pressure comfort measurements were analysed for shoulder pads of the specific segmentation types; vacuum moulded, cut-segmented and unsegmented. Across the results, the standard deviation from the mean was in the range of 0 – 2.9 mmHg, with a mean standard deviation of 0.3 mmHg. The highest standard deviation, 2.9 mmHg was obtained for garment F on participant 2 and garment C on participant 6. Both garment C and F were vacuum moulded Gilbert rugby shoulder padded tops which indicated that they provided the least consistent pressure comfort. The pressure comfort measurements were analysed in combination with garment fit observations per segmentation type.

4.3.8 Vacuum Moulded Pads

Garments C, E, F and G comprised of shoulder padding with vacuum moulded segmentation. The widest range of pressure comfort values between 0 – 11.0

mmHg were recorded as documented in Table 9. The results were outside of the ideal pressure comfort range defined for rugby shoulder padding in this research as > 0 mmHg and < 3.2 mmHg. Values of 0 mmHg were reported for all vacuum moulded garments, excluding garment F fitted to Participant 4, suggesting that the pads lifted away from the shoulder. Figure 44 exhibits technical drawings of the different vacuum moulded pads.

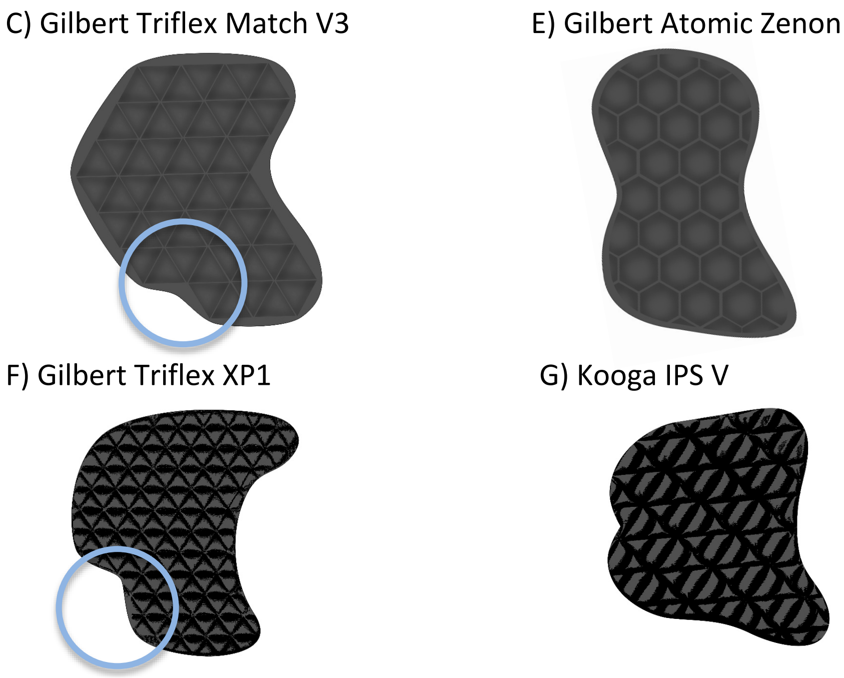


Figure 44: Technical drawings of the shoulder pads from garments C, E, F and G; regions that lifted away from the body are circled (Authors Own Image, 2018)

The range of results recorded for garment F were between 0 – 4.3 mmHg in the front shoulder region, the lowest recorded range of the vacuum moulded tops. Garment F had the most suitable fit on Participant 4 who had the median chest circumference and therefore was suited to a wider variety of tops. Therefore, garment F generated the most consistent pressure comfort of its segmentation type, providing the best pressure comfort during body movements. Garment F had a 76.0 cm pad circumference and Figure 44 shows that it was the largest of the vacuum moulded pads. Due to its larger pad circumference, it is possible that garment F would have also provided more protective coverage across the shoulder region.

Contoured regions of the vacuum moulded tops were found to pucker or sit away from the shoulder and are circled in Figure 45. In particular, garment C appeared loose fitting and seemed to pucker, as seen in Figure 45 on participant 4 in the stationary position. Garment C had the second largest pad circumference of the vacuum moulded pads, its scale may have contributed to its poor conformability to the curved shoulder region. In Table 9 garment C generated 0 mmHg pressure in the stationary position, indicating that its loose fit was a factor for the recorded poor pressure comfort. Garment C also generated 0 mmHg values across three arm raises whilst fitted to participant 6, despite having the largest chest circumference, it appears puckered in Figure 46. Loose fitting padded garments have potential to move or slide during sport participation and under impact, where the padding slides out of place that shoulder region is more vulnerable (Watkins and Dunne, 2014).

Figure 45: Front view of vacuum moulded shoulder pads fitted to participant 4; regions that lift away from the body are circled (Authors Own Image, 2018)

Figure 46: Front and back view of garment C fitted to participant 6; a region that lift away from the body is circled (Authors Own Image, 2018)

Garment G had the tightest fit of the vacuum moulded tops, fabric surrounding the shoulder padding was seen to pull as illustrated in Figure 45. The graph in Figure 47 showed that peak pressure comfort values generated for participants 1, 4 and 5 were higher than the ideal range, recorded measurements were within the range of light medical compression. In contrast, the graph in Figure 48 showed that the range between 0 – 7.3 mmHg recorded in the back of the vacuum moulded shoulder pads was lower than the front. Figure 45 illustrated that all four pads were less conforming to the shoulder in the front than the back (Figure 49). The results and observations confirmed that greater consistency in pressure comfort of vacuum moulded shoulder pads were identified for those that provided greater fit.

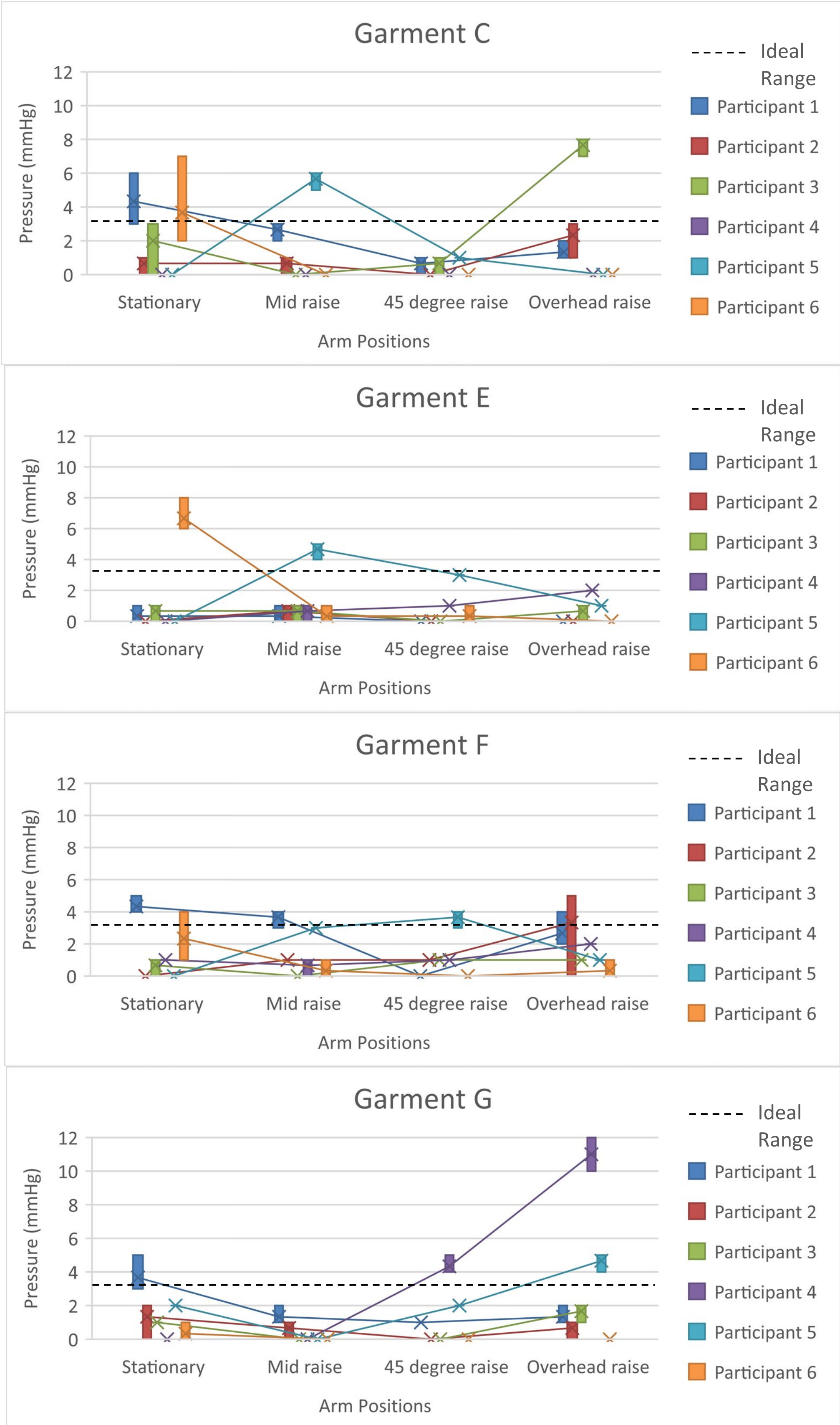


Figure 47: Mean pressure comfort measurements obtained from the front shoulder landmarks of the vacuum moulded pads

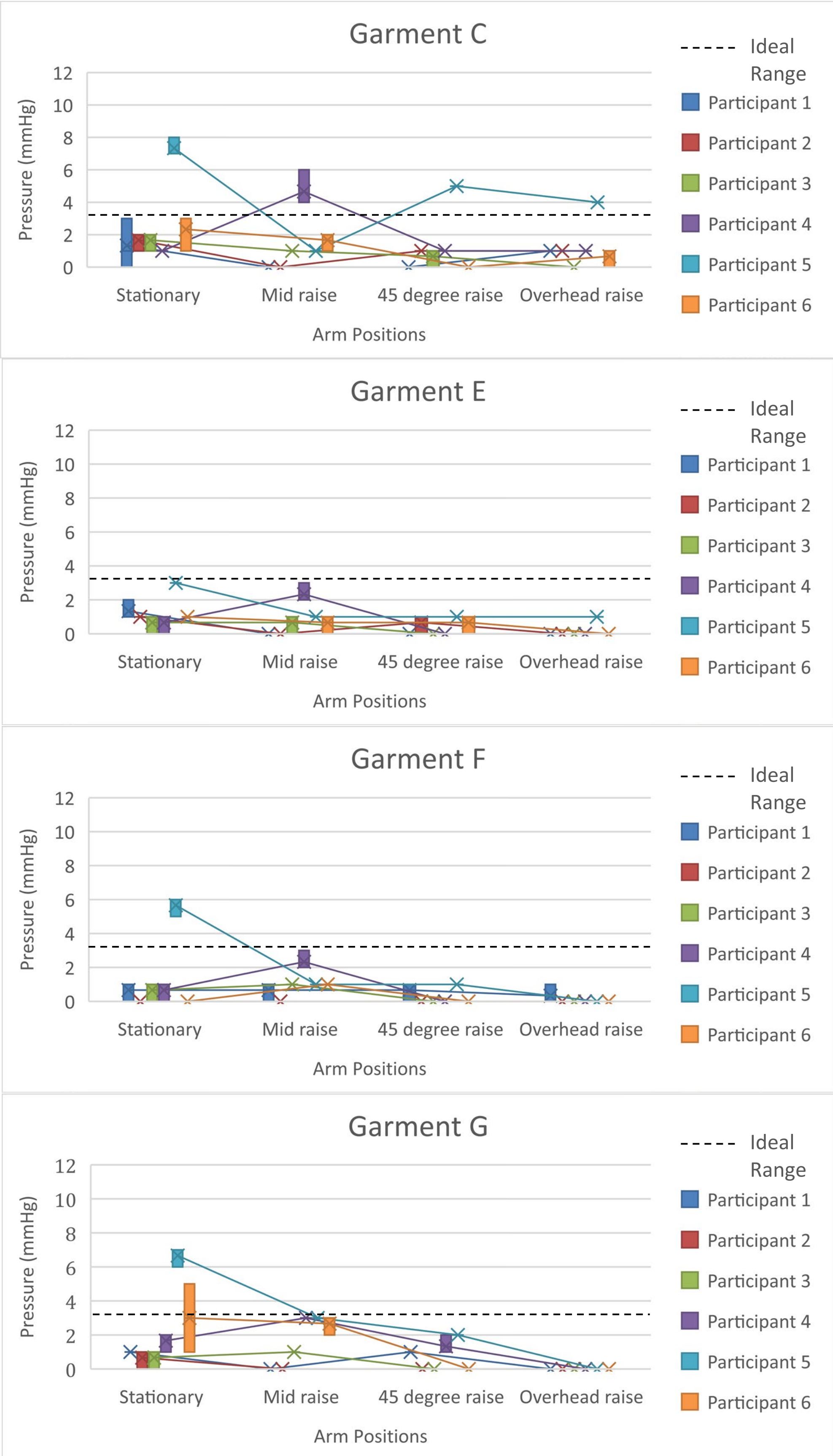


Figure 48: Mean pressure comfort measurements obtained from the back shoulder landmarks of the vacuum moulded pads

Figure 49: Back view of vacuum moulded shoulder pads fitted to participant 4 (Authors Own Image, 2018)

The brand sizing recommendations of the vacuum moulded garments were not consistent. In particular, the three Gilbert vacuum moulded tops appeared to offer varying fit to individual participants, also seen from the back view in Figure 49. Garment E had the smallest pad circumference and was loose across the torso of participant 4, shown in Figure 49, which may have enabled the generation of lower pressure values. The shoulder pads of garment F had the greatest fit of the Gilbert vacuum moulded tops but the garment was otherwise loose. Garments C and G were a tighter fit across the torso than F, but generated higher pressure in the shoulder region. In summary, vacuum moulded pads that provided more consistent pressure comfort and shoulder padding fit were loose across the main body of the garment.

4.3.9 Cut Segmented Pads

Garments B, C and I were comprised of shoulder pads with cut segmentation. It was not known whether the method used to slice segments out of the pad was laser cut or die-cut as both can produce that effect (Hui, 2014; Gordon et al., 2015). The cut patterns varied in shape, sliced widths, unit cell scale and the pads varied in overall shape and circumference, as shown in Figure 50. Cut segmented pads conformed better than vacuum moulded, as the padding did not pucker, reflected by the low range of pressure comfort measurements recorded between 0 – 8.3 mmHg. Nonetheless, the overall range was outside the ideal pressure range defined for rugby shoulder padding.

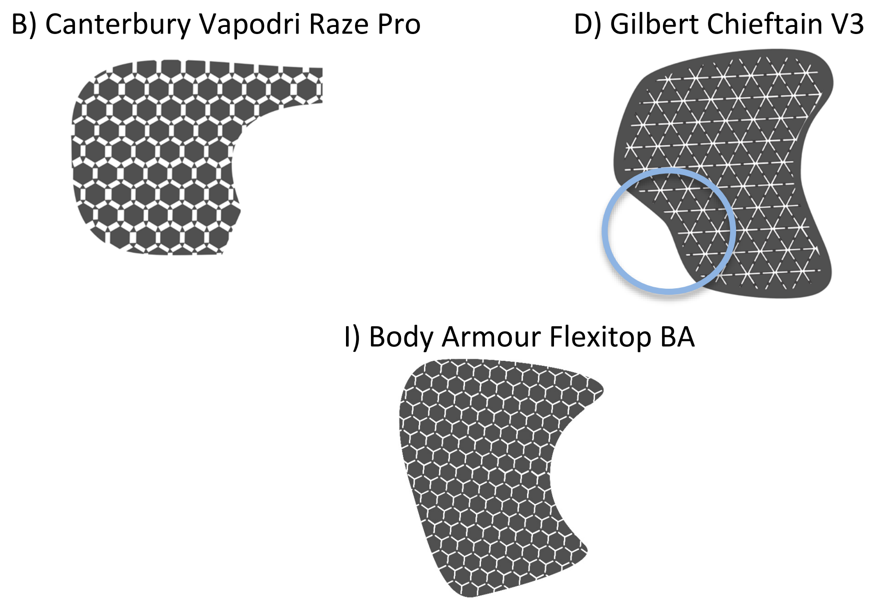
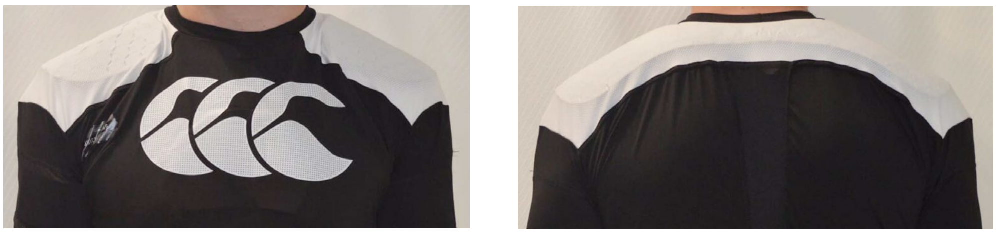


Figure 50: Technical drawings of the shoulder pads from garments A, D and I; a curved region that lifts away from the body is circled

The fit of the cut-segmented garments differed such that garment I was the tautest and garment D the loosest. In general, it was observed that garment B had the best fit across the participants of the cut segmented pads, having the smallest pad circumference was likely to contribute to its conformability to the curved shoulder region. However, there was also evidence to suggest that the unit cell of garment B pads had auxetic elements; its geometry enabled the pad to be compressed improving its conformability. The segments of garment B were comprised such that the triangular unit cells rotate around the hexagon unit cells, which enabled the cut widths between segments to close laterally under compression. However, the geometry of the pad did not enable lateral expansion, restricting its NPR characteristics.

Figure 51 showed that the shoulder pads of garment B had a good observed fit on participant 2, whose chest circumference was smallest as well as participant 6, whose was the largest. The similar observed fit of garment B across the participants was reflected by a similar pressure comfort pattern which emerged for all six participants in the front shoulder region, shown by the graph in Figure 52. Pressure was highest in the stationary position, when the arms were level with the shoulders. In mid and 45 degree arm raises, pressure decreased and finally increasing during the overhead position.

a)



b)

Figure 51: Front and back view of garment B fitted to participants a) 2 and b) 6 (Authors Own Image, 2018)

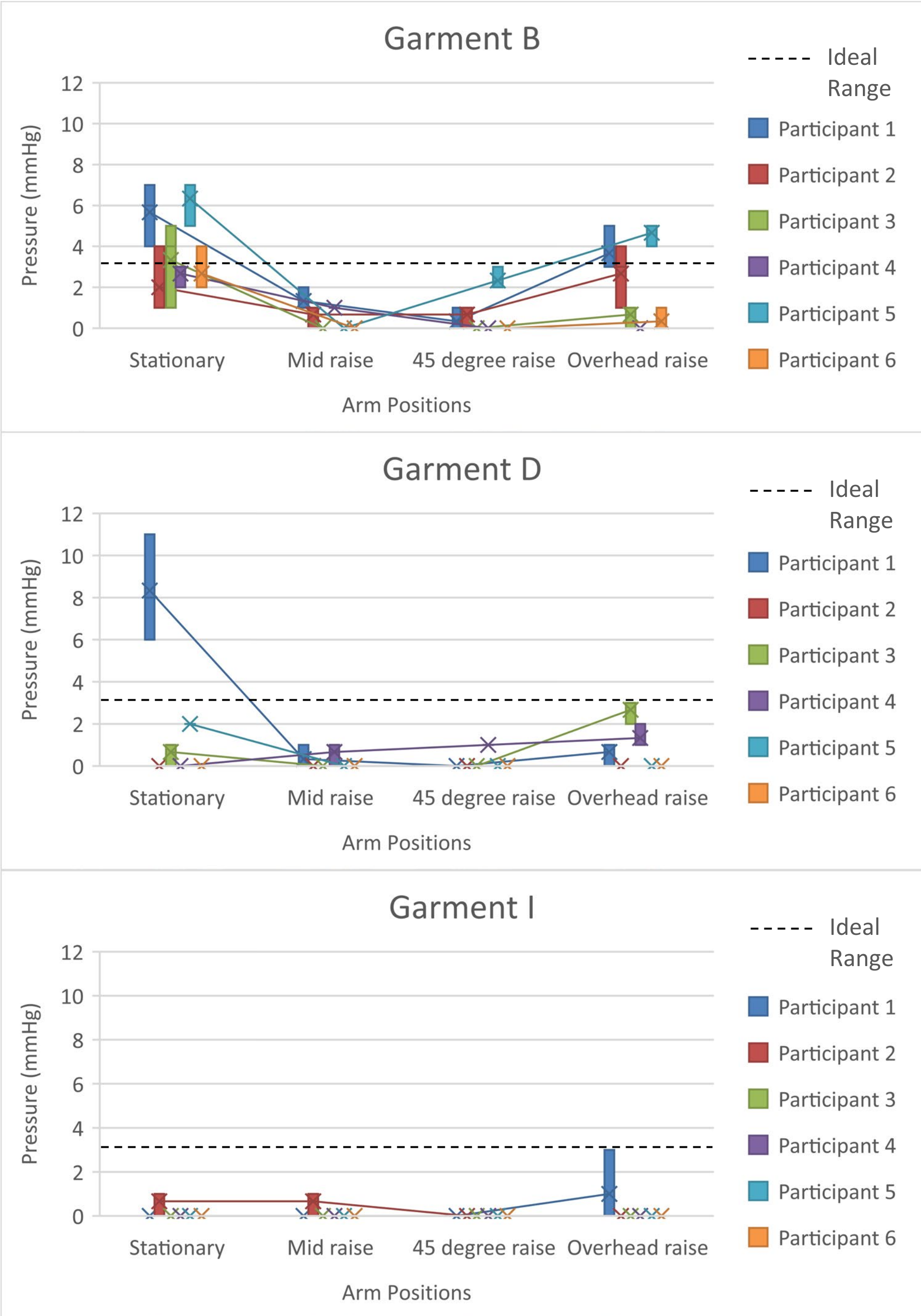


Figure 52: The Mean pressure comfort measurements obtained from the front shoulder landmarks of the cut segmented pads

Figure 53 shows that the padding of garment D splayed away from the shoulder at the front of participant 6 who had the largest chest circumference. The poor fit was reflected by the low pressure 0 mmHg reported to the front shoulder region for participant 6 as well as participant 2, as seen in Figure 52. Garment D was too loose for all the participants. The shoulder padding of garment D had the largest circumference; therefore it was considered bulky. In addition, garment D had a loose fit and both factors seemed to prevent it from conforming to the participants' shoulder regions.

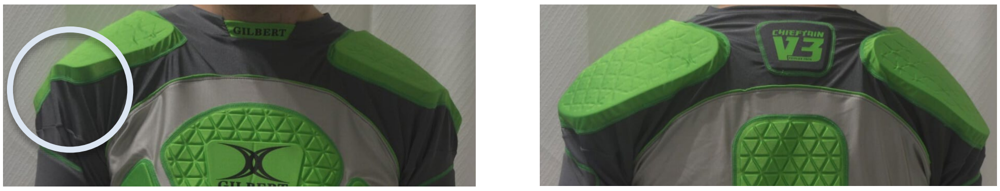


Figure 53: Front and back view of garment D fitted to participant 6; a region that lifted away from the body is circled (Authors Own Image, 2018)

In Figure 54, garment I appeared tight fitted to both participant 1 who had one of the smallest chest circumferences and participant 5, one of the largest. Despite appearing tight, garment I obtained a range between 0 – 1.0 mmHg in the front shoulder region and its fabric appeared to bunch, lifting away from the front shoulder. In contrast, the graph in Figure 55 showed that garment I was the only top for which pressure levels were higher in the back, by up to six times and the back shoulder region appeared tighter than the front. The spaces between the segments of garment I were the smallest of the cut segmented pads, 0.1 cm, whereas those of garment B were 0.4 cm and garment D had cut widths of 0.3 cm. Larger cut widths appeared to enable padding to conform better to the curved shoulder region.

a)

b)

Figure 54: Front and back view of garment I fitted to participants a) 1 and b) 5 (Authors Own Image, 2018)

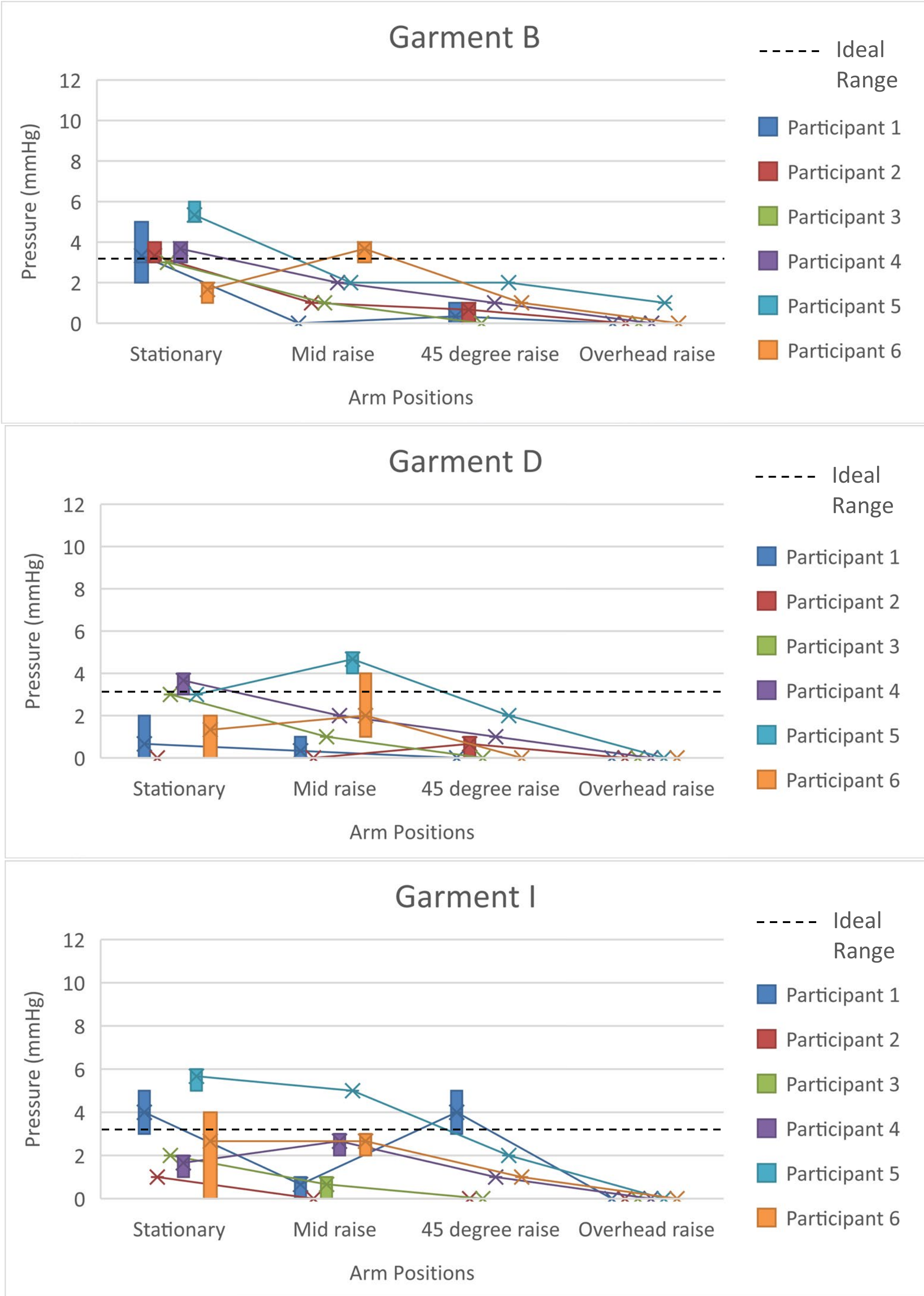


Figure 55: Pressure comfort measurements obtained from the back shoulder landmarks of the cut segmented pads

The segmentation pattern of garments B and I had the appearance of a repeated honeycomb. However, the cut segments that created a honeycomb appearance differed. Figure 50 showed that the repeated slices of padding B were rectangular, repeated six times in a honeycomb orientation and then repeated throughout the pad. Whereas, garment I was cut segmented by three 3-pointed stars in a honeycomb orientation. The segmentation pattern of garment D had a triangular appearance, produced by slicing three 6-pointed stars and was the least conforming garment in Phase II. Findings for the cut segmented shoulder pads indicated that honeycomb patterns offered the greatest conformability but that specifically garment B was the most conformable to all participants.

4.3.10 Unsegmented Pads

Garment H comprised of one entirely unsegmented shoulder pad, embedded to both pocketed shoulder regions. The padding of garment A was unsegmented but each shoulder region comprised of four separately pocketed pads, therefore it was categorised as unsegmented. Figure 56 displayed the quartered effect of garment A compared to the entirely unsegmented padding of H. The range of pressure comfort values obtained for the unsegmented pads was 0 – 7.3 mmHg. The range of pressure measurements recorded for unsegmented pads were the lowest of the three pad segmentation categories.

A) Canterbury Vapodri Raze H) Body Armour Tech Vest BA

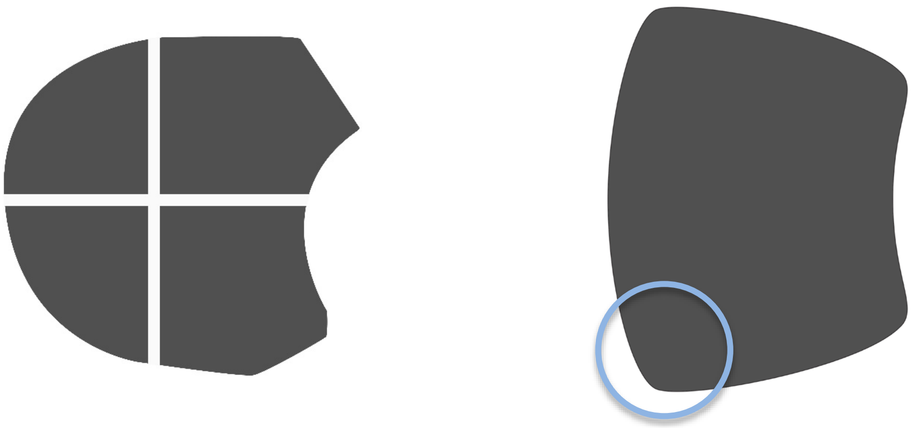
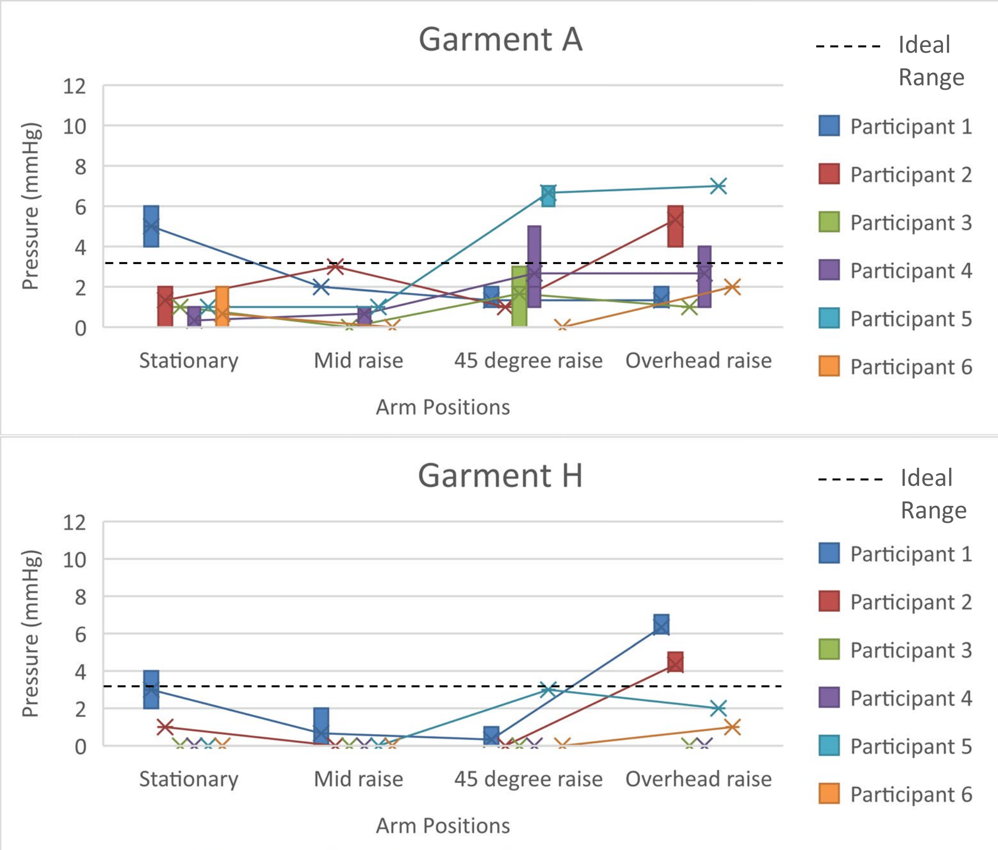


Figure 56: Technical drawings of the shoulder pads from garments A and H; a region that lifted away from the shoulder is circled (Authors Own Image, 2018)

A similar pattern was observed in the pressure values obtained for garment A and H in the front and back shoulder regions. The graph in Figure 57 shows that in the back shoulder region, pressure was higher in the stationary position, decreasing with each consecutive raised arm position. This finding was also identified for the vacuum moulded and cut segmented padding, suggesting that neither conformed well to the back of the shoulder during the four arm raises. In the back shoulder region of garment A fitted to participant 5, obtained the range between 1.0 – 7.3 mmHg, the least consistent pressure reported for the unsegmented pads. Figure 58 showed that the back shoulder region was a tight fit on participant 5 in the stationary position, causing garment A to generate higher pressure than H.

a) front



b) back

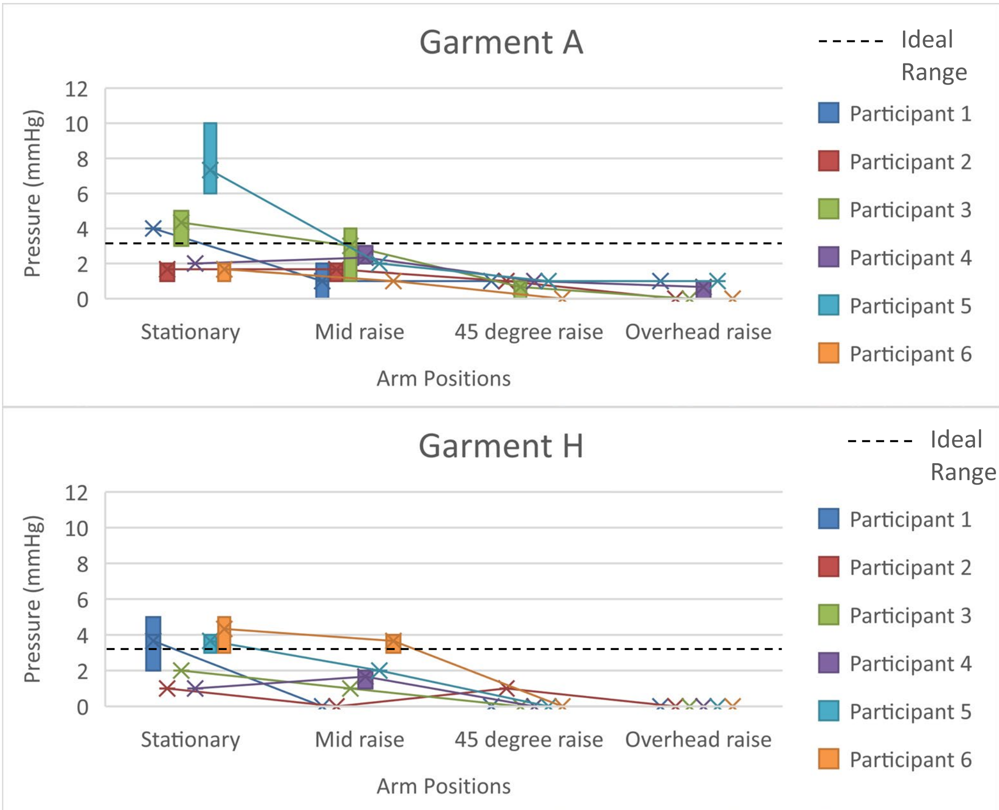
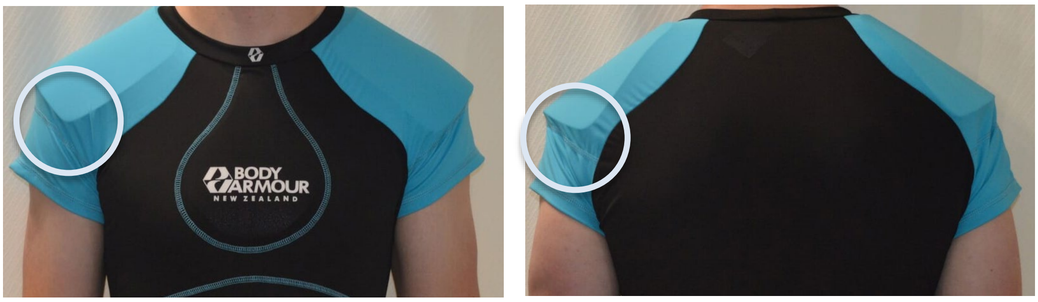


Figure 57: Mean pressure comfort measurements obtained from the a) front and b) back shoulder landmarks of the non-segmented pads

Figure 58: Front and back view of garment A fitted to participant 5 (Authors Own Image, 2018)

Garment H generated pressure ranging from 0 – 6.3 mmHg, marginally lower than the range between 0 – 7.5 mmHg recorded for garment A. The shoulder pads of garment H were found to splay away from the body which caused the surrounding fabric to pucker and lift away from the body, as seen in Figure 59. In particular, the results showed that in the mid arm raise, five out of six participants experienced 0 mmHg pressure. The poor fit of garment H was shown on both participant 5 with a chest circumference close to the upper limit in the study and participant 2 whose was closest to the lower limit. Therefore, the pressure range obtained across the participants in garment H may have been lower than in garment A because the foam pads splayed, lifting away from the body. Where the shoulder padding of garment H was entirely unsegmented, it had a bulky appearance and the short sleeves seem to pull away from both participants upper arms in Figure 59.

a)



b)

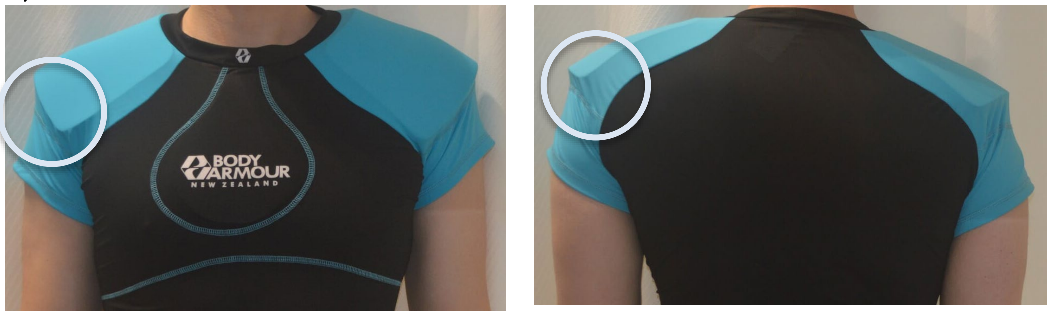


Figure 59: Front and back view of garment H fitted to participants a) 2 and b) 5; regions that lifted away from the shoulder are circled (Authors Own Image, 2018)

Pressure was not recorded within the ideal range for the unsegmented tops , the one exception was Garment A fitted to participant 4. Figure 60 showed that garment A fitted to participant 4, appeared to conform well to the curvature of the shoulder and across the participant's chest. However, loose fabric appeared to bunch where it surrounded the shoulder pads in the front region and where the top of the arms met the padding. Garment A offered the lowest pressure comfort range but the shoulder padding was of the smallest circumference, 59.5 cm which would have benefited its conformability. The circumference of the remaining eight pads were in the range 70.3 – 82.1 cm. In particular unsegmented garment H had a 72.3 cm pad circumference and might have provided more protective coverage.

Figure 60: Front and back view of garment A fitted to participant 4 (Authors Own Image, 2018)

A similar pressure range and pattern was generated for the unsegmented pads but the fit of the garments varied. In particular, garment H splayed away from the shoulder region of all six participants whereas garment A appeared to conform well. It was likely that garment A had improved fit because its pad circumference was 22% smaller than garment H. The fit of garment A also benefitted by the quartering of the each pad into four individual pockets per shoulder. In contrast, garment H had a poorer fit but might have provided more protective coverage due to its larger pad circumference.

4.3.11 Summary of Fit Analysis of Current Rugby Shoulder Padding

Through Phase II patterns in the conformability of different types of shoulder padding were identified. In particular, vacuum moulded garments that offered a close fit to the wearer led to poor pressure comfort, in the most extreme case pressure reached that of light medical compression wear. Bunching of shoulder padding was associated with vacuum moulded and not with cut or unsegmented shoulder pads. Splaying was seen across the three shoulder padding categories, and was most extreme for the unsegmented garment H in which it lifted away from the shoulder. However, Garment A did not splay, both because the pad was quartered and the individual pieces were separately pocketed. However, it had the smallest pad circumference and would have offered the least protective coverage.

In Phase II it was identified that the laser cut shoulder pads had the greatest observed fit as a category. However, garment D was oversized for all the participants and therefore did not conform well to the shoulder region. Therefore, it was difficult to compare how conformable the triangular segmentation pattern of garment D was against the honeycomb segmentation of garments B and I. However, the honeycomb segmentation pattern of B and I appeared to conform well to the shoulder region of the participants. Of the cut-segmented honeycomb pads, garment B offered more consistent pressure comfort across the participants.

Summary of Key Findings

Phase II established that current rugby shoulder padding can cause poor pressure comfort where it does not conform well to curved body regions. It was identified that all three segmentation types provided poor pressure comfort that was not in the ideal range or inconsistent during the active body positions associated with rugby participation. In addition, all three segmentation types led to splaying of the pads away from the shoulder region. Segmented shoulder pads were found to provide the best fit, as the pads did not pucker or bunch, which was a fit issue seen across the vacuum moulded pads. However, the non-segmented pad led to greater lifting away from the shoulder than segmented pads.

4.4 Phase III: Development of Auxetic Shoulder Padding

Previous research has identified problems with the conformability and comfort of PPE for impact and collision sports (Finch et al., 2001; Rome, 2019;). In particular, wearer discomfort was reported for rugby shoulder padding but evidence based on user perceptions and garment analysis is limited (Nayak et al., 2017). Segmentation is often used to reduce the restrictiveness and limited conformability of bulky body padding. Webster and Roberts (2009) indicated that one route to improvement is to provide more consistent pressure levels. Auxetic structures can enable conformability to curved regions (Lakes, 1987; Wang and Hu, 2014) but it is not yet known how the impact protection of auxetic structures differ when subject to synclastic curvature.

Phase I of the research identified that thermal and weight comfort were perceived by rugby shoulder padding wearers as the most unsatisfactory realms of comfort. Generally, the sample were dissatisfied with rugby shoulder padding comfort, the highest satisfaction was identified for perceived fit and protective comfort. Fit and protection were also identified as the most critical realms of comfort to respondents and over half of the respondents never wore rugby shoulder padding. Phase II determined that rugby shoulder padding was bulky and non-conforming to the shoulder region as it provided poor pressure comfort and puckered across the fabric and PPE. However, rugby shoulder padding with laser-cut segmentation led to the greatest conformability, maintaining consistent pressure comfort measurements and not puckering.

Phase III critically analysed shoulder padding with auxetic segmented patterns to investigate how far it offered an enhanced compromise between conformability and protection. The behavioural differences of five shoulder pads with four auxetic and one non-auxetic internal structure were investigated in part one of Phase III. Four physical test methods were used to determine which structure obtained the lowest peak forces and conformability. The physical testing included tensile, dimensional, pressure comfort and impact tests. The identified internal structure was manipulated through cut widths, anisotropy and rib lengths, producing nine samples in part two and the physical tests were repeated.

4.4.1 Part 1 – Determining Behavioural Differences Between Auxetic Structures Through Physical Testing

Five EVA shoulder pads were cut-segmented with auxetic internal structures that were chiral (C001), rotating squares (RS002), 3-pointed star (3PS003) and 4-pointed star (4PS004) as well as a non-auxetic pattern (HC005) (Figure 61) for comparison. Rugby shoulder padding is subject to impact over a curved body region under dynamic movements related to rugby Union participation (Harris and Spears, 2010). Part 1 investigated which shoulder padding internal structure offered the greatest conformability as well as impact tests over flat and curved surfaces. The consistency and scale of each pad's lateral displacement were assessed; recording data under synclastic curvature on a mannequin, during tensile strength tests. Data was measured at the widest (T and B) and narrowest (M) horizontal landmarks and longest vertical landmark (L) (Figure 61). Furthermore, the pressure comfort provided by each shoulder pad was measured through different arm raises to identify conformability through body movement.

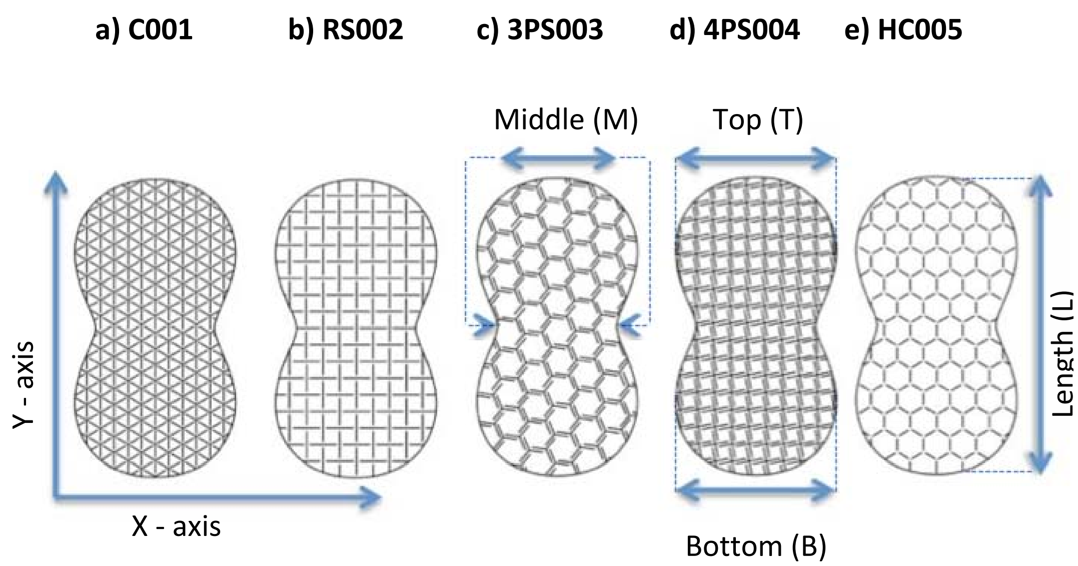


Figure 61: Technical drawings of the five pad samples with segmented laser cut shapes: a) chiral, b) rotating squares, c) 3-pointed star, d) 4-pointed star and e) honeycomb (Authors Own Image, 2019)

4.4.1.1 Tensile Displacement (Test 1)

Under tensile displacement, non-auxetic structures can laterally contract, often at different rates throughout the structure (Joun et al., 2007). In contrast, auxetic structures can laterally expand (Kolken and Zadpoor, 2017) at different rates, rather than consistently throughout the pad. Therefore, it is possible that a shoulder pad with an internal structure that opens out at a concentrated area would offer less coverage at that region than one that opens out consistently. The results in Table 10 presented the landmarks T, M, B of the five shoulder pads at maximum tensile displacement. Maximum tensile displacement was reached when visible or audible signs of failure were identified for the internal structures, the full set of results are shown in appendix F. The percentage difference in lateral displacement of landmarks T, M, B were also presented for the five pads; a lower percentage represented a more consistent opening mechanism throughout the pad, rather than at concentrated regions.

Table 10: Lateral expansion at maximum tensile displacement

Auxetic Shoulder Pads	Tensile Displacement (cm/%)	Time (secs)	Lateral Displacement			Difference Between Middle and Mean of T and B (%)
			Top (T)/ Bottom (B) (cm)	Mean Of T and B (cm/%)	Middle (M)(cm/%)	
C001	8.1/54	50	2.4/2.6	2.5/21	4.1/48	27
RS002	5.4/36	32	1.9/2.1	2.0/17	2.2/26	9
3PS003	6.2/ 41	46	0.8/1.6	1.2/10	2.6/31	21
4PS004	8.3/55	51	1.2/1.1	1.2/10	2.2/25	15
HC005	1.3/9	7	- 0.4 / - 0.3	- 0.4/- 3	- 0.4/- 5	- 2

*measured to an assumed accuracy of 0.1 cm

Table 10 confirmed that HC005 was not auxetic, it had negative lateral expansion across all three-landmark widths at maximum tensile displacement (Domaschke et al., 2019). In contrast, all four of the pads with auxetic laser cut patterns (001 – 004) were confirmed auxetic, indicated by their positive lateral expansion at T, M, B. Due to the figure 8 shape of the pads and the clamping mechanism (Mizzi et al., 2020), the centre (M) was determined the narrowest and subject to the greatest lateral expansion. Therefore, a lower percentage lateral displacement was calculated at the widest widths, T and B. The five pads led to varying percentage displacements between the narrowest and widest widths which ranged from – 2% to 27%, for HC005 and C001 respectively. Table 10 showed that the internal structure of RS002 had the most consistent opening mechanism under tensile displacement, which can be seen in Figure 62.

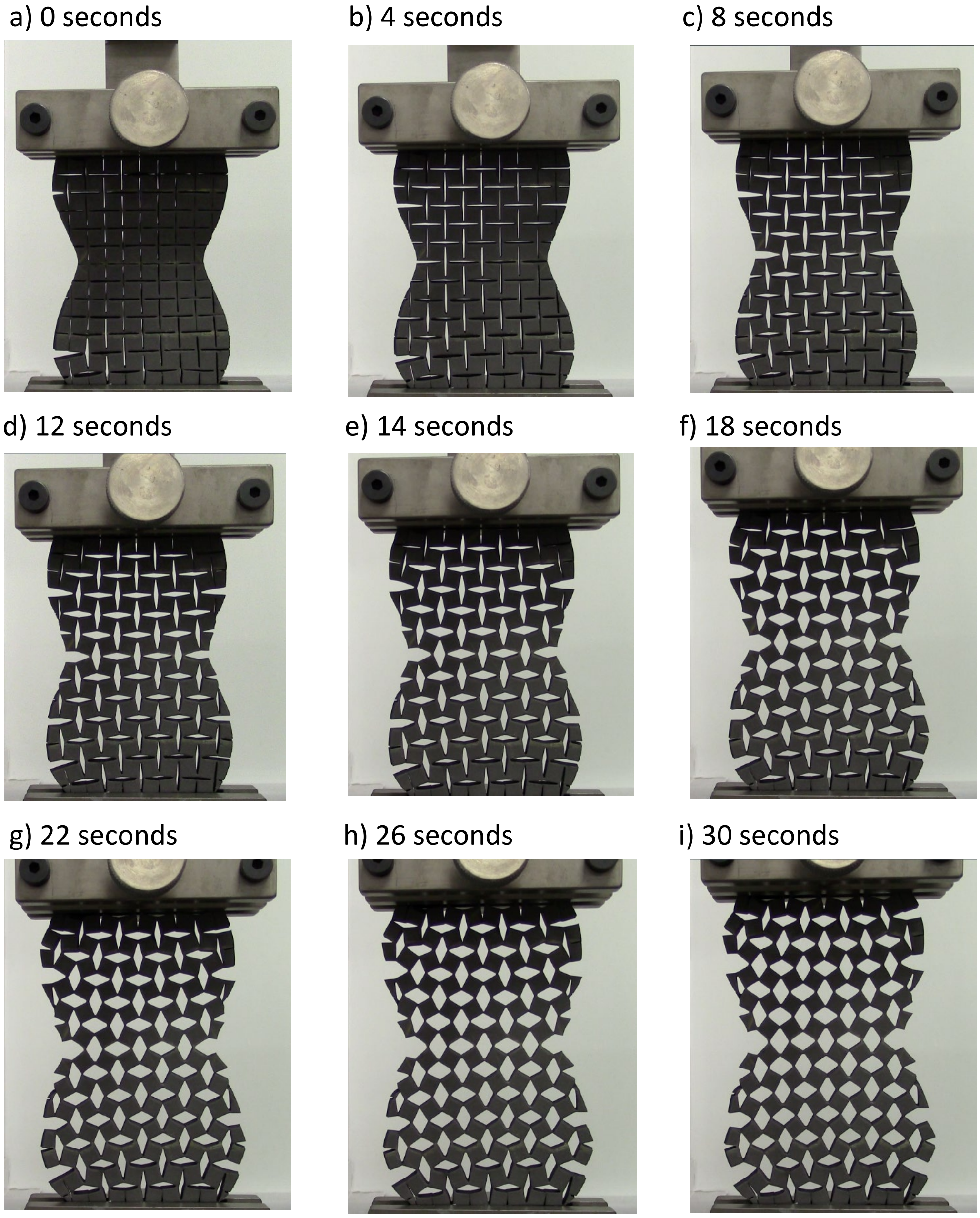


Figure 62: A sequence of the internal structure of RS002 opening at 4 second increments up to maximum tensile displacement (Authors Own Image, 2019)

A range of maximum tensile and lateral displacements were recorded for all five pads, as the individual opening mechanisms differed, as shown in Figure 63. In particular, the internal structures of C001 and 3PS003 appeared to open out considerably at the narrowest width M, compared to the widest T, B. Table 10 indicates that at maximum displacement, the greatest percentage difference between the narrowest and widest widths of the five pads was obtained for C001 (27%) and 3PS003 (21%). Therefore, the results confirmed that opening of the internal structure of C001 and 3PS003 were the least consistent. C001 and 3PS003 were found to have the greatest lateral expansion at M, as such it was possible that the central region (M) would offer the least protective coverage.

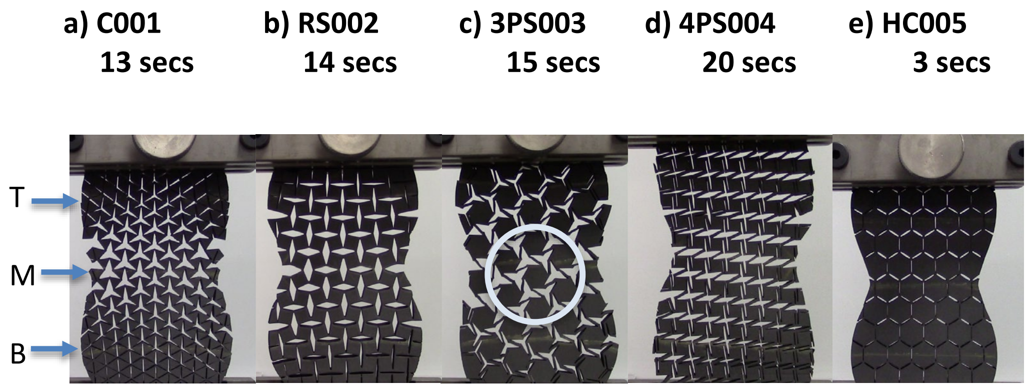


Figure 63: The five segmented pads at the timed mid-point, circled is an opened region of 3PS003 (Authors Own Image, 2019)

At full extension as seen in Figure 64, 4PS004 generated 55% tensile displacement, the highest, whereas 9% was recorded for HC005 which was the lowest. However, at maximum tensile displacement (Table 10), 4PS004 obtained the lowest lateral expansion of the auxetic pads. Furthermore, images d in Figures 63 and 64 showed that 4PS004 opened out unsymmetrically, appearing to twist to the right and left, known as shearing (Lipton, 2018). In contrast, RS002 had the lowest percentage difference (9%) between M and T, B of the auxetic pads, opening evenly and consistently, as illustrated in image b in Figures 63 and 64. Due to obtaining the lowest percentage difference in lateral expansion between T, M, B, it was possible that RS002 would offer more protective coverage to the wearer.

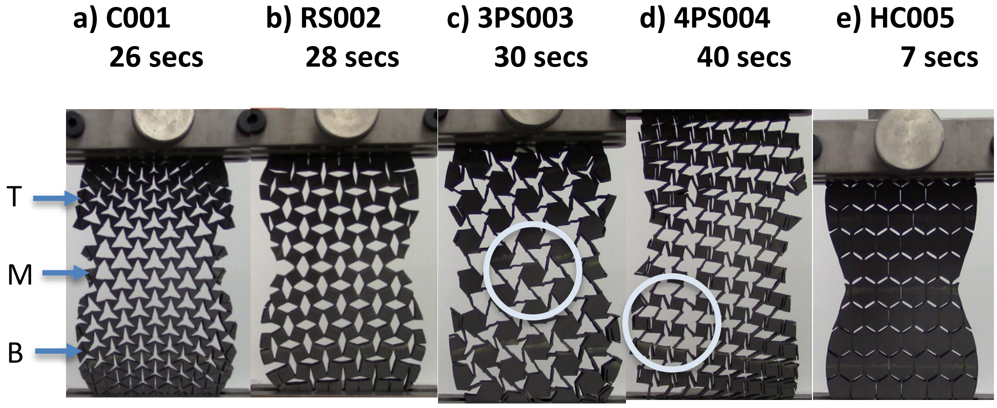


Figure 64: The five segmented shoulder pads at maximum tensile displacement, circled is an opened region of 3PS003 as well as the shearing of 4PS004 (Authors Own Image, 2019)

RS002 recorded high lateral expansion at the widest widths (17%) and narrowest (26%) and its opening mechanism was identified as the most consistent. Due to the consistent lateral expansion of RS002 it was possible that it would provide more protective coverage throughout the pad. During sport, skin can extend up to 50% at different regions (Senthilkumar et al., 2012) and sportswear is required to support this extension and recovery. The lateral and tensile displacement of RS002 was less than 50% but otherwise greater than the non-auxetic alternative HC005. Manipulating the internal structure of RS002 has potential to enhance its lateral and tensile displacement yet maintain its opening out consistency.

4.4.1.2 Lateral Expansion of Pads Fitted to a Mannequin (Test 2)

Table 11 presents dimensional changes to the shoulder pads when fitted to a mannequin. Dimensional change is recorded as the displacement at the shoulder pads vertical length (L) as well as the widest (T, B) and narrowest widths (M). Figure 65 presented one of the five shoulder pads (HC005) embedded within the pocketed shoulder region of a rugby top, fitted to a mannequin, with arms at its side. The test identified which samples generated positive dimensional change (auxetic) and conversely negative dimensional change (non-auxetic) when curved over the shoulder (Timoshenko and Goodier, 1970). Of the five pads, lower percentage difference between dimensional change at T, M, B had potential to offer more protective coverage, opening out consistently rather than at concentrated regions of the pad.

Table 11: Lateral expansion of five shoulder pads fitted to a mannequin

Five Shoulder Pads	Test	Length Displacement (cm/%)	Lateral Displacement			Difference Between M and T,B (Mean) (%)
			Top (T)/ Bottom (B) (cm)	Mean Of T and B (cm/%)	Middle (M) (cm/%)	
C001	**1**	2.6/12	0.3/0.4	0.4/3	- 0.2/- 2	5
	2	2.6/12	0.2/0.3	0.3/3	- 0.3/- 4	7
	3	2.8/13	0.3/0.3	0.3/3	- 0.2/- 2	1
RS002	**1**	2.4/11	0.3/0.4	0.4/3	1.1/13	10
	2	2.5/12	0.4/0.4	0.4/3	1.0/12	9
	3	2.4/11	0.4/0.5	0.5/4	1.1/13	9
3PS003	**1**	2.4/12	0.2/0.0	0.1/1	0.8/9	8
	2	2.6/12	0.5/- 0.2	0.2/2	0.8/9	7
	3	2.4/12	0.5/- 0.1	0.2/2	0.7/8	6
4PS004	**1**	1.5/7	0.2/- 0.4	- 0.1/- 1	0.0/0.0	- 1
	2	1.4/7	0.1/- 0.5	- 0.2/- 2	- 0.1/- 1	- 1
	3	1.6/7	0.1/- 0.6	- 0.3/- 3	- 0.1/- 1	- 2
HC005	**1**	0.8/4	0.0/- 0.1	- 0.1/1	- 0.4/- 4	- 5
	2	1.1/5	0.0/0.0	0.0/0	- 0.6/- 7	- 7
	3	1.0/5	0.0/- 0.1	- 0.1/1	- 0.6/- 7	- 8

*measured to an assumed accuracy of 0.2 cm

a) front (showing T)

b) side (showing M)

c) back (showing B)

d) side (showing L)

Figure 65: HC005 (non-auxetic comparison) inserted within the pocketed region of a rugby top and fitted to a size XL men's mannequin (Authors Own Image, 2019)

The percentage difference between manual measurements at T, M, B presented in Table 11 indicated that C001, 3PS003, 4PS004 and HC005 decreased at one or more landmarks. Tolerances in garment construction are typically between 0.1 and 0.3 cm (Montazer et al., 1987), as such the measurements were taken to an assumed accuracy of 0.2 cm. In addition, C001, 4PS004 and HC005 all generated negative dimensional change with the additional 0.2 cm assumed accuracy. In contrast, RS002 generated positive dimensional change at all three widths in the three tests, even by subtracting the 0.2 cm assumed accuracy. Therefore, RS002 was the only auxetic shoulder pad not subject to negative dimensional change.

RS002 had a 10% difference in test 1 and 9% difference in tests 2 and 3 between the lateral expansion of T, M, B, the largest of the five shoulder pads. However, the other shoulder pads resulted in negative lateral expansion which was not ideal. Therefore, RS002 was found to conform better to the shoulder as it enabled positive lateral expansion throughout the measured landmarks. In contrast, HC005 and 4PS004 generated the greatest difference in negative lateral displacement between T, M, B. Figure 65, Image d showed that during the tensile test 4PS004 opened out unsymmetrically throughout the shoulder pad. The unsymmetrical opening to the internal structure of 4PS004 led to shearing. HC005 and 4PS004 also generated the lowest length displacement and therefore were considered the least conforming to the shoulder region and provided the least consistent opening mechanism.

RS002 and 3PS003 recorded similar lateral expansion and percentage difference between T, M, B. However, the opening mechanism of 3PS003 was less consistent than RS002, such that expansion recorded at B was negative and expansion at T was positive in all three tests. Where 3PS003 was found to contract (negative expansion) on one side of the pad by opening out, it was likely that it would have led to less protective coverage in the region that opened out. RS002 performed the best of the five shoulder pads, conforming well to the shoulder region of the mannequin. However, manipulation of the internal structure of RS002 could be improved to enhance the opening consistency between T, M, B and in turn potentially increase protective coverage.

4.4.1.3 Pressure Comfort (Test 3)

Pressure comfort is a leading factor in the wearer's sensation of comfort in tight fitting garments (Das and Alagirusamy, 2010). There are no optimal pressure comfort measurements for shoulder padding (Li and Wong, 2006), therefore the ideal pressure comfort range defined as > 0 mmHg and < 3.2 mmHg in Phase II was used and referred to in Phase III. In addition, current research has identified that changing pressure levels during body movement can cause discomfort (Li and Wong, 2006). The five shoulder pads were embedded within the pocketed region of a rugby top, fitted to a mannequin for reliability and repeatability. However, this meant that the results were not comparable with those of pads in Phase II which conducted assessments on human participants. Pressure comfort was measured at four arm raises that reflected the shoulder mechanisms required to perform rugby tasks. Table 12 presented the mean pressure comfort measurements obtained from the front and back shoulder region across the four arm positions.

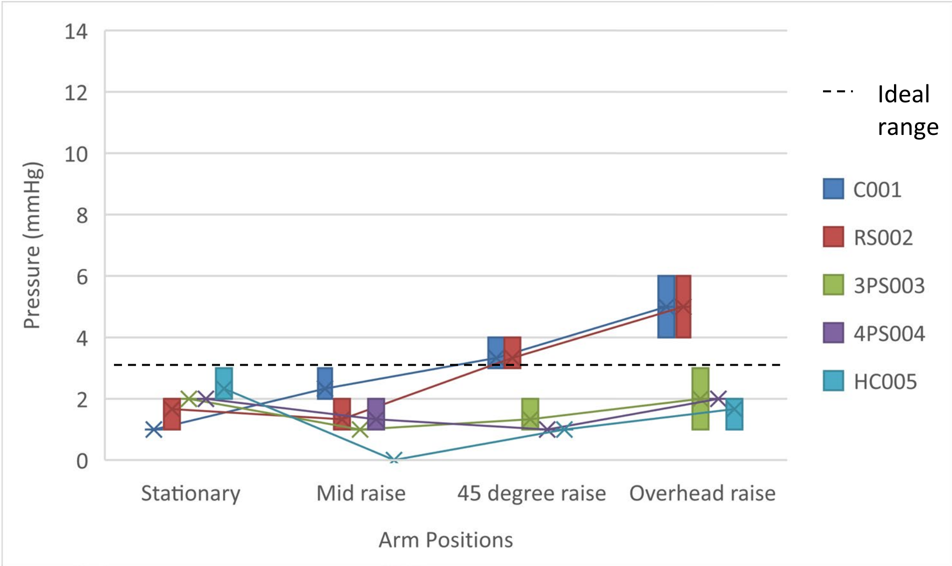
Table 12: The mean pressure comfort measurements of the five pads

		The Four Arm Positions (mmHg)			
Pads	**Shoulder Region**	**Stationary**	**Mid**	**45 Degrees**	**Over Head**
C001	Front	1.0	2.3	3.3	5.0
	Back	3.0	2.0	1.0	1.0
RS002	Front	1.7	1.3	1.7	3.0
	Back	1.3	1.0	1.7	1.7
3PS003	Front	2.0	1.0	1.3	2.3
	Back	1.0	1.0	1.0	1.0
4PS004	Front	2.3	1.3	1.0	2.0
	Back	2.0	1.0	2.0	0.7
HC005	Front	2.3	0.0	1.0	1.7
	Back	1.0	1.0	2.0	2.3

The results in Table 12 showed that the pressure comfort values obtained from the front shoulder landmarks across the five pads ranged between 0.0 – 5.0 mmHg. In the back shoulder region, a range between 0.7 – 3.0 mmHg, which was smaller than the front and within the ideal pressure comfort range. The front shoulder landmark of all five pads obtained the highest pressure measurements in the overhead and stationary arm positions. Whereas, lower pressure comfort was recorded at mid and 45-degree arm positions. Therefore, lower pressure was typically obtained through positions in which the arm was relatively level with the shoulder line (mid and 45 degree raises) and the pads were less concave or convex.

The graph in Figure 66 showed that C001 obtained the highest range of pressure comfort values, outside of the ideal range for rugby shoulder padding. Therefore, of the five pads C001 was the least conformable. It was also identified from the results that the auxetic shoulder pads gained higher mean pressure comfort values in the front than the back-shoulder region where it was less conforming. HC005 obtained 0 mmHg in the mid-raise position and therefore was found to lift away from the shoulder region. Research has shown that PPE discomfort can cause distraction (Tirloni et al., 2018), as such changing pressure comfort levels between body movements could too. Therefore, C001 and HC005 were the most likely to cause discomfort that could lead to distraction from performing rugby tasks and movements safely and properly.

a)



b)

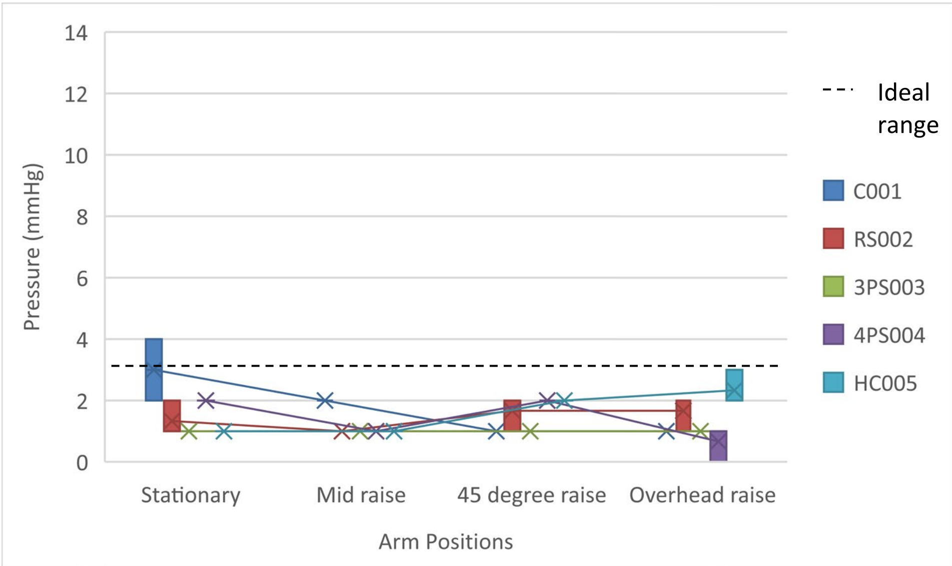


Figure 66: Mean pressure comfort measurements (mmHg) of five shoulder pads at a) front and b) back shoulder landmark across four arm raises

Between arm positions, RS002 and 3PS003 measurements ranged between 1.3 – 3.0 mmHg and 1.0 – 2.3 mmHg respectively, providing the most consistent pressure comfort. In the stationary position 3PS003 had a marginally higher difference of 1.0 mmHg between its front and back landmark than RS002. There was a difference of 0.5 mmHg recorded for RS002 in the stationary position between front and back pressure comfort measurements. 4PS004 also obtained pressure values within the good pressure comfort range for shoulder padding, yet the range was higher and therefore less consistent. In summary, RS002 and 3PS003 were considered to offer the greatest conformability, providing consistency in pressure comfort with potential to cause less distraction during rugby union participation.

4.4.1.4 Impact Tests (Test 4)

Further to the assessment of conformability, the five shoulder pads were subject to impact tests. Auxetic open cell foams have been subject to impact under synclastic curvature by Foster et al., (2018). However, closed cell foam with auxetic structures cut into them have not yet been subject to impact when under synclastic curvature. Therefore, impact on closed cell with auxetic structures were impact tested on flat, cylindrical and domed anvils for comparison. The results displayed the peak forces obtained for the five shoulder pads subject to an impact of 5 J in the same position. Tests were repeated three times following 60 second intervals (World Rugby, 2019) and the mean was calculated as seen in Table 13.

Table 13: Peak force (N) from impact tests of five shoulder pads over three anvils

Shoulder Pads	Anvil	Test 1	Test 2	Test 3	Mean
C001	Flat	2180	2257	2287	2241
	Cylindrical	4259	5444	5484	5062
	Domed	9280	10389	10672	10114
RS002	Flat	2155	2229	2266	2217
	Cylindrical	4480	4514	4700	4565
	Domed	8800	10089	10376	9755
3PS003	Flat	2256	2338	2367	2320
	Cylindrical	3894	4622	4899	4472
	Domed	8763	9958	10272	9664
4PS004	Flat	2213	2289	2308	2270
	Cylindrical	4333	5197	5407	4979
	Domed	9255	10288	10571	10038
HC005	Flat	2170	2256	2291	2239
	Cylindrical	4001	4078	4140	4073
	Domed	9225	9418	9683	9442

The mean peak forces obtained over the flat anvil ranged between 2217 – 2320 N, RS002 and 3PS003 had the lower and upper bound of the range respectively, as shown in Table 13. The mean peak forces obtained for pads impacted over the cylindrical anvil ranged from 4073 – 5062 N, the lower and upper bound of the range was identified for HC005 and C001 respectively, which were around double those obtained from the flat anvil. A range between 9442 – 10113 N (HC005 and C001 had the lower and upper bound of the range respectively) was obtained for pads impacted over the domed anvil around triple those obtained from the flat anvil. Graphs in Figure 67 demonstrated that peak forces increased with the curvature of the anvil. Under curvature the pads internal structures opened out and as a result, it is possible this could decrease the pads protective coverage of the shoulder region when in use. Despite the differences of internal structures, the mean peak forces for RS002 and 3PS003 were higher, but comparable over curved anvils to HC005, the non-auxetic shoulder pad.

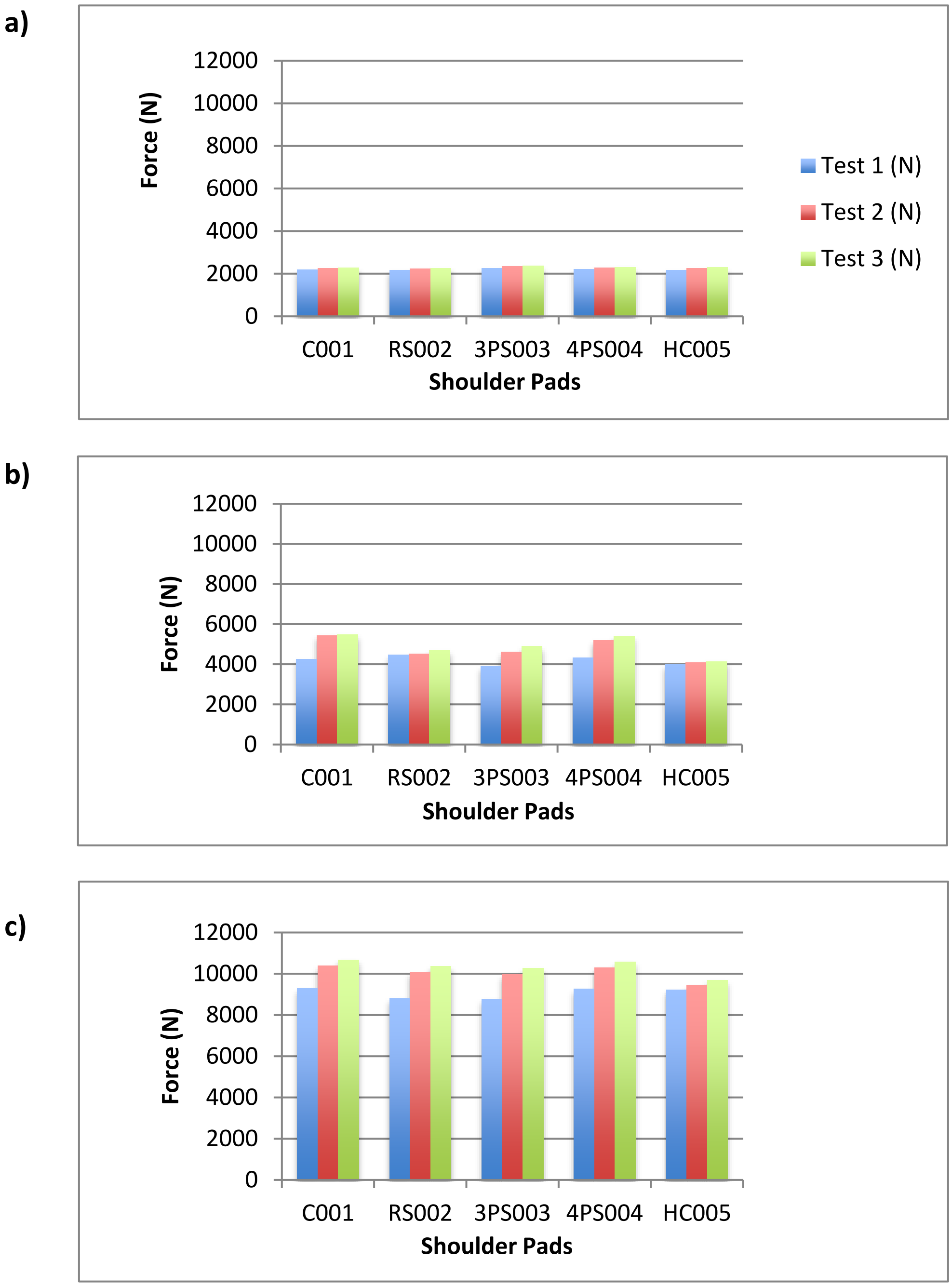


Figure 67: Forces (N) from the impact tests of five shoulder pads over three anvils; a) flat, b) cylindrical and c) domed

HC005 to obtain the lowest range of peak forces over curved anvils between impact tests 1 and 3 (Figure 67, graphs b and c). Therefore, the non-auxetic shoulder pad HC005 obtained lower peak forces between impact tests compared to those that opened out due to having an auxetic internal structure (structures 001 – 004). This finding suggested that commercial padding did not degrade as quickly as the auxetic pads; some degradation was observed but images were not taken. Peak forces obtained over a flat surface were otherwise very similar for all five pads. This finding further implied that peak forces were dependent on the opening mechanism of the pad as they were similar prior to opening.

C001 and 4PS004 exhibited the highest peak forces for impacts over curved anvils (cylindrical and domed). It was identified through the tensile test that C001 had the least consistent opening mechanism of the pads. Therefore, under increased curvature (Figure 67, graphs b and c) it was possible that the internal structure of C001 opened out the most. In contrast, RS002 was not comprised of ligaments, due to its arrangement of non-intersecting cut lines and was identified through the tensile test as having a consistent opening mechanism. Therefore, it was possible that a consistent opening mechanism enabled RS002 to obtain the lowest mean peak forces over a flat anvil of the five pads.

Over curved anvils RS002 obtained the third lowest mean peak forces of the shoulder pads. 3PS003 obtained the second highest mean peak forces over curved anvils, despite attenuating the lowest peak force over the flat anvil. The internal structures were controlled by maintaining the same rib length and therefore, the unit cell scales varied slightly. Due to the hexagonal structure of 3PS003 which had the largest number of sides, the unit cells also appeared the largest of the auxetic internal structures. Therefore, over curved surfaces, the larger unit cell scale of 3PS003 may have enabled lower peak forces.

HC005 performed the best during the impact tests, where lowest peak forces were recorded over curved anvils and the second lowest over the flat anvil. Lower peak forces were obtained for internal structures with shorter connecting points between unit cells as well as internal structures with larger unit cells/protective segments. Therefore, of the auxetic shoulder pads, RS002 was identified as having performed the best across tests on flat and curved anvils. 3PS003 obtained lower peak forces over curved anvils but the highest peak forces over the flat anvil. Due to 3PS003's hexagonal internal structure it appeared to have the largest unit cell scale but longer connecting points, the inconsistency may have been due to unit cell positioning between the different anvils. Manipulating RS002 to have larger unit cells has potential to obtain lower peak forces over curved anvils.

4.4.1.5 Behavioural Differences Between Auxetic Structures Summary (Part 1)

In summary, of the five pads, the rotating squares internal structure enabled the most consistent lateral expansion in the tensile test and when fitted to a mannequin. In contrast, HC005, the non-auxetic shoulder pad decreased in length laterally during the tensile test and dimensional change test. RS002 and 3PS003 had the most consistent pressure comfort levels and therefore performed the best in the three tests relating to conformability (tests 1 – 3). Second to the non-auxetic internal structure, RS002 also exhibited lower peak forces under impacts on all three anvils. Therefore, of the five shoulder pads, RS002 presented the best compromise between reducing peak forces and enhancing conformability.

Summary of Key Findings

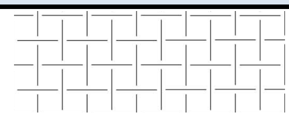
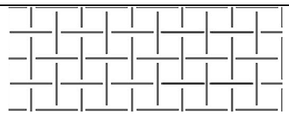
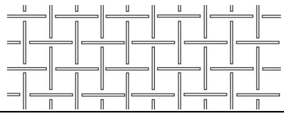
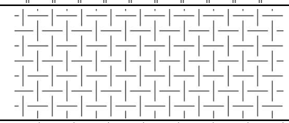
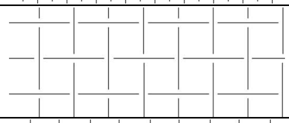
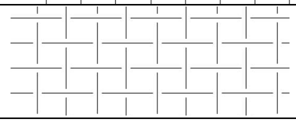
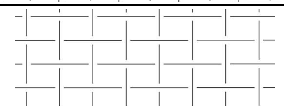
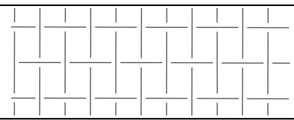
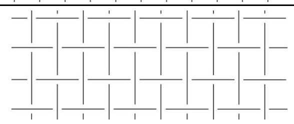
Through the tensile test, the most consistent lateral expansion was identified for RS002. High lateral expansion was also identified for C001 and 3PS003 but opening out of the internal structures was less consistent. In contrast, 4PS004 opened out unsymmetrically, appearing to shear and HC005 decreased at the three measured widths. Through insertion within the pocketed region of a rugby top fitted to a mannequin, in test 2, RS002 was the only pad that enabled positive dimensional change at all landmarks. HC005 and C001 were not found to obtain the ideal pressure comfort range in test 3. Of the pads within the ideal pressure comfort range, RS002 and 3PS003 obtained the smallest range of values, therefore providing the most consistent pressure comfort.

3PS003 obtained the lowest over the flat anvil but the highest over curved, whereas RS002 which had the most consistent opening mechanism of the auxetic pads obtained consistently low peak forces over the three anvils out of the auxetic pads. The quantity of foam removed through segmentation was not examined through this research and as such it was unknown whether this affected peak forces. However, when placed over cylindrical and domed anvils respective auxetic structures opened out to different degrees, affecting the quantity of foam exposed to the impact striker. This research examined opening mechanisms and found a correlation between consistent opening mechanisms with auxetic structures which obtained lower peak forces over curved anvils compared to auxetic structures with inconsistent opening mechanisms. However, as HC005 was segmented with a non-auxetic pattern it was unable to open out and as such exhibited the lowest peak forces over curved anvils and second lowest over the flat anvil in test 4.

4.4.2 Part 2 – Manipulation of the Rotating Squares Structure for Rugby Shoulder Padding Segmentation

Researchers have identified that tailoring the geometry of an auxetic structure can change its mechanical properties and behaviour (Mizzi et al., 2020). Therefore, in Part 2, manipulation to the rotating squares structure was performed to determine the suitability in relation to conformability and impact protection. Table 14 displays the manipulated internal structures of the rotating squares segmentation pattern by anisotropy, cut widths and rib lengths. The nine samples were subject to identical test and analysis methods performed in Part 1. Through geometric manipulation the most suitable internal structure for segmenting rugby shoulder padding obtaining low peak forces as well as the greatest opening consistency and conformability will be recommended.

Table 14: The nine rotating squares manipulated internal structures

Shoulder Pads	Rotating Squares Internal Structure Manipulation (cm)	Cross-section
RS006	Original Rotating Squares internal structure	
RS007	Laser cut widths: 0.25	
RS008	Laser cut widths: 0.4	
RS009	Rib lengths: 0.5	
RS010	Rib lengths: 1.5	
RS011	Anisotropic - rib length aspect ratio: 1.5 (horizontal): 1.0 (vertical)	
RS012	Anisotropic - rib length aspect ratio: 2.0 (horizontal): 1.0 (vertical)	
RS013	Anisotropic - rib length aspect ratio: 1.0 (horizontal): 1.5 (vertical)	
RS014	Anisotropic - rib length aspect ratio: 1.0 (horizontal): 2.0 (vertical)	

4.4.2.1 Tensile Displacement (Test 1)

Table 15 presents percentage lateral displacement (expansion) across the top (T), bottom (B) and middle (M) of each of the nine pads, at maximum tensile displacement. The results calculated for the maximum tensile and lateral displacement of the nine pads were visible or audible signs of failure were identified for each individual internal structures. The difference between lateral displacement at the narrowest (M) and widest (T, B) widths was also determined. Shoulder pads with the lowest percentage difference in lateral displacement between landmarks T, M, B would potentially offer more protective coverage. The results reveal how manipulating an auxetic geometry can affect its opening consistency under tensile displacement. Table 15 presents the data from test 3, the full set of results (tests 1, 2 and 3) are shown in appendix G.

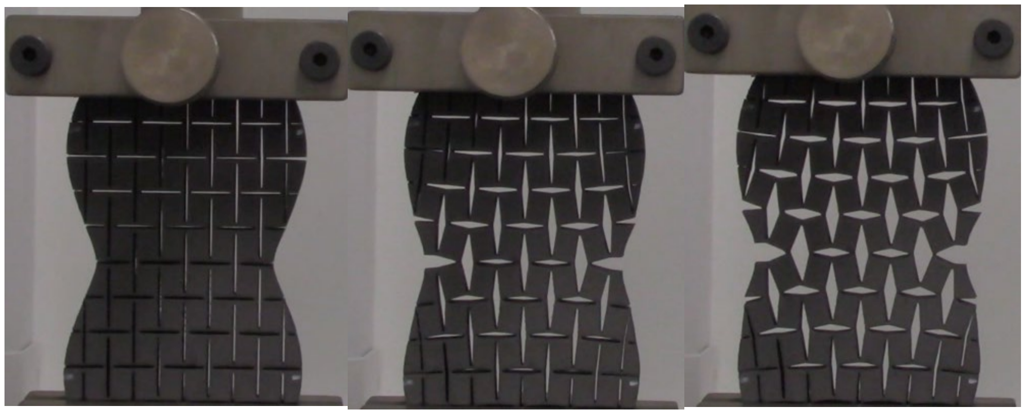
Table 15: Lateral expansion at maximum tensile displacement

Nine pad shapes	Tensile Displace -ment (cm/%)	Time (secs)	Lateral Displacement			Difference Between M and Mean of T, B (%)
			Top (T)/ Bottom (B) (cm)	Mean Of T, B (cm/%)	Middle (M)(cm/%)	
RS006	6.8/45	51	2.0/1.9	2.0/16	2.0/24	8
RS007	4.6/31	29	0.6/1.2	0.9/8	2.0/24	16
RS008	5.5/37	34	0.7/1.1	0.9/8	1.9/22	14
RS009	4.7/31	29	0.2/0.4	0.3/3	1.2/14	11
RS010	5.5/37	27	1.3/0.5	0.9/8	3.2/38	30
RS011	6.4/43	38	1.4/1.5	1.5/12	2.7/32	20
RS012	4.6/31	26	1.2/1.0	1.1/9	3.0/35	26
RS013	6.5/43	39	0.9/1.0	1.0/11	1.7/15	4
RS014	8.9/59	53	0.7/0.8	0.8/6	0.6/7	1

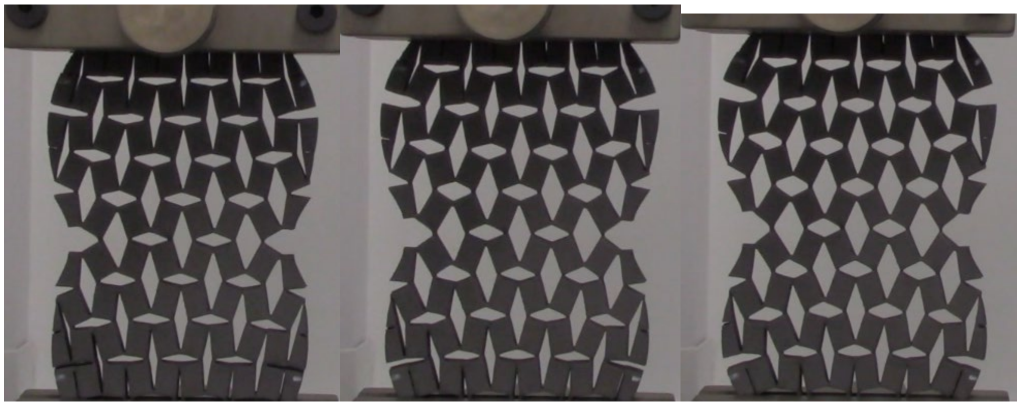
*measured to an assumed accuracy of 0.1 cm

Table 15 presents that positive lateral expansion was obtained at maximum tensile displacement for all three width landmarks T, M, B, confirming that all nine shoulder pads were auxetic. RS009 and RS006 respectively recorded 3% to 16% lateral displacement, at the widest landmark widths (mean T, B). Percentage lateral displacement was highest at M and ranged between 7% to 38%, RS014 and RS010 obtained the lower and upper bound of the range respectively. Difference between the lateral displacements of T, M, B ranged from 1% to 30%; RS014 was the lowest and RS010 the highest. Therefore, the latter opened the least consistently, providing potentially less consistent protective coverage throughout the pad. Figure 68 presents anisotropic pad RS012 with horizontally orientated ribs increased by 2.0 cm opening when subject to tensile force over 4 second increments.

a) 0 seconds b) 4 seconds c) 8 seconds



d) 12 seconds e) 16 seconds f) 20 seconds

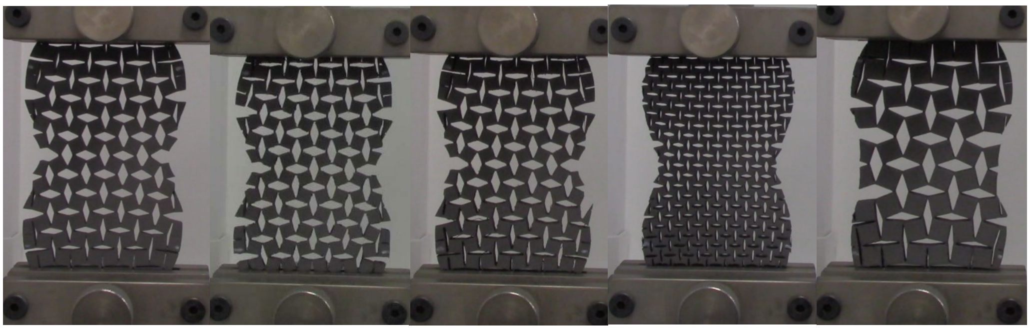


g) 24 seconds

Figure 68: The internal structure of anisotropic pad RS012 with horizontally orientated ribs increased by 2.0 cm in an opening out sequence of 4 second increments up to maximum tensile displacement (Authors Own Image, 2019)

Figure 69 showed that there was a 13 seconds difference between the shoulder pads with the smallest (RS009) and highest (RS014) tensile displacement at the timed mid-point. Figure 69 also showed that RS009 had the least consistent opening mechanism and that RS014 was the most consistent. RS009 was manipulated such that it had the shortest rib lengths (0.5 cm) of the nine shoulder pads. The percentage lateral displacement of RS009 (Table 15) was the lowest of the pads at the widest landmark (mean T, B: 3%) and second lowest at the central width (M: 14%). Therefore, decreasing rib lengths led to an observed decrease in the tensile and lateral displacement of the shoulder pad, in turn potentially restricting the extension of the stretch garment it could be joined to.

a) RS006 18 secs **b) RS007 12 secs** **c) RS008 13 secs** **d) RS009 9 secs** **e) RS010 15 secs**



f) RS011 15 secs **g) RS012 14 secs** **h) RS013 16 secs** **i) RS014 22 secs**

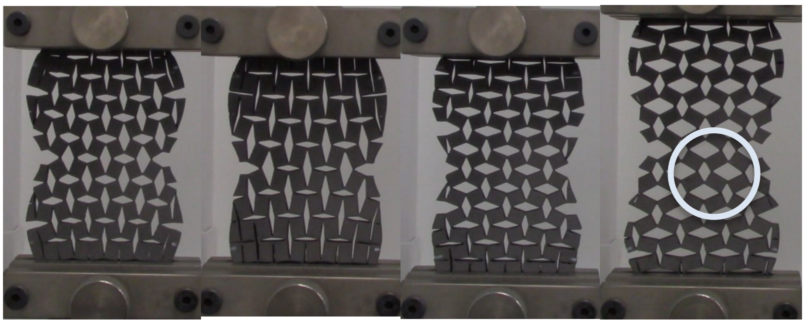
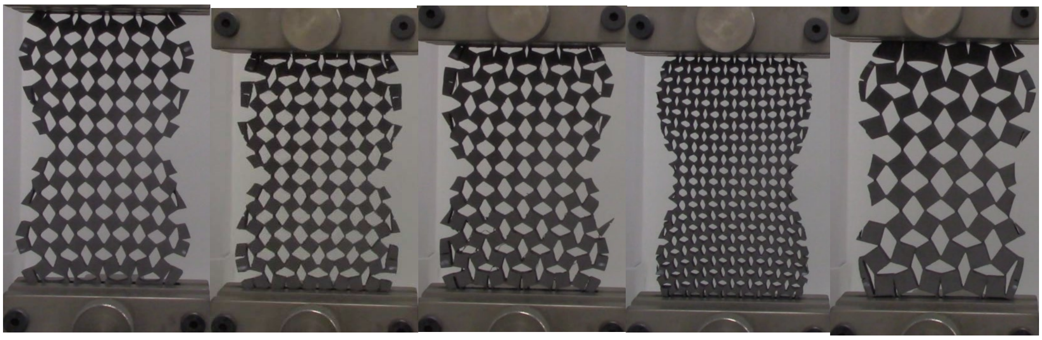


Figure 69: The nine segmented pads at the timed mid-point, circled is an opened region of RS014 (Authors Own Image, 2019)

The nine shoulder pads opened at different rates between the widest (T, B) and narrowest (M) widths (Figure 69) at the timed mid-point of tensile displacement. The lowest percentage difference in lateral displacement between the narrowest (M) and widest (T, B) landmarks was identified for RS013 (4%) and RS014 (1%) in table 15 and observed in Figure 69. For the remaining 7 shoulder pads, the narrowest width M expanded at a greater rate than the widest widths, T, B as observed in Part 1. RS014 obtained the lowest lateral expansion at M and the highest tensile displacement of the pads, due to having the longest horizontally orientated ribs. Therefore, RS014 was found to be less conformable under tensile displacement as it generated the lowest lateral expansion.

The maximum tensile displacement of RS009 ended at 18 seconds, whereas RS014 opened out for 44 seconds, Figure 70 showed that the former was less conforming. Shoulder pads with increased laser cut widths of 0.25 cm (RS007) and 0.4 cm (RS008) obtained the second lowest tensile displacement of the nine pads. Lateral displacement at M was 14% for RS007 and 16% for RS008, comparative to the original rotating squares internal structure (RS006). In contrast, lateral displacement at the widest widths (mean T, B) of RS007 and RS008 was approximately half of RS006 (8%). The ribs of RS006 were cut to the diameter of the laser beam which was 0.5 cm. In order to increase the cut widths of RS007 and RS008 the ribs were drawn as rectangles instead of lines. Therefore, increasing the cut widths of the rotating squares structure led to less conformability but the results may have been influenced by the diameters of the laser beam.

a) RS006 37 secs **b) RS007 24 secs** **c) RS008 26 secs** **d) RS009 18 secs** **e) RS010 29 secs**



f) RS011 29 secs **g) RS012 27 secs** **h) RS013 32 secs** **i) RS014 44 secs**

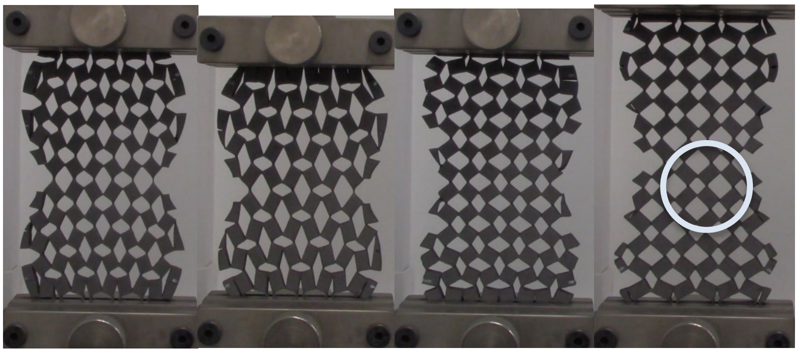


Figure 70: The nine segmented shoulder pads at maximum tensile displacement, circled is an opened region of RS014 (Authors Own Image, 2019)

Shoulder pads manipulated by anisotropy, RS011 – 014, obtained the greatest tensile displacement. However, a difference of 20% and 26% was respectively recorded for RS011 and RS012 between lateral expansion at the widest T, B and narrowest M widths of those with increased horizontally orientated ribs. Therefore, opening of RS011 and RS012 was less consistent than the unmanipulated shoulder pad, RS006, which had a difference of 8% between T, M, B. At maximum tensile displacement, it was observed that RS010, RS012 and RS014 had the most consistent opening mechanisms of the nine shoulder pads. RS010, RS012 and RS014 were manipulated such that they had the longest ribs, opening out to a larger scale than the other internal structures.

It was identified that by increasing the cut widths of the internal structure, the difference between lateral displacement was increased and in turn so was opening inconsistency. Altering rib lengths of RS009 and RS010 also lead to a reduction in the consistency of lateral displacement as well as reduced tensile displacement. Anisotropic manipulation enabled a greater consistency in lateral displacement, especially pads with horizontally orientated ribs, but also led to low overall lateral displacement. The shoulder pads with increased vertically orientated ribs obtained greater percentage lateral displacement, but lower tensile displacement. In summary, manipulating the internal structure of the rotating squares auxetic shoulder pad led to behavioural differences, but the largest and most consistent lateral displacement was identified for the unmanipulated structure, RS006.

4.4.2.2 Lateral Expansion of Pads Fitted to a Mannequin (Test 2)

Table 16 presented lateral expansion to the nine auxetic shoulder pads embedded within a rugby top. Lateral expansion to the nine shoulder pads was recorded at the vertical length (L) as well as widest (T, B) and narrowest widths (M) when fitted to the mannequin. Shoulder pads with a lower percentage difference between the lateral displacement at T, M, B would be representative of an internal structure comprising of a consistent opening mechanism, ideal for protective coverage.

Table 16: Lateral expansion of five shoulder pads fitted to a mannequin

Five Shoulder Pads	Test	Length Displacement (cm/%)	Lateral Displacement			Difference Between M and T,B (Mean) (%)
			Top (T)/ Bottom (B) (cm)	Mean Of T and B (cm/%)	Middle (M) (cm/%)	
RS006	**1**	2.0/10	1.3/0.2	0.8/7	0.4/5	2
	2	2.1/10	1.1/0.2	0.7/6	0.3/4	2
	3	2.0/10	1.4/0.2	0.8/7	0.3/4	3
RS007	**1**	1.1/5	0.0/0.0	0.0/0	0.0/0	0
	2	1.1/5	0.0/0.0	0.0/0	0.1/1	1
	3	1.3/6	0.0/0.1	0.1/1	0.0/0	1
RS008	**1**	1.1/5	- 0.1/0.4	0.2/2	0.4/6	4
	2	1.1/5	- 0.1/0.5	0.2/2	0.3/4	2
	3	1.2/6	- 0.3/0.2	- 0.1/- 1	0.4/6	7
RS009	**1**	0.7/3	- 0.2/- 0.2	- 0.2/- 2	0.0/0	2
	2	0.7/3	- 0.3/- 0.2	- 0.3/- 2	- 0.1/- 1	1
	3	0.6/3	- 0.3/- 0.1	- 0.2/- 2	- 0.1/1	3
RS010	**1**	1.0/5	- 0.2/0.0	- 0.1/- 1	0.1/1	2
	2	1.4/7	- 0.1/0.0	- 0.1/- 1	0.2/2	3
	3	1.1/5	0.0/0.1	0.1/1	0.2/2	1
RS011	**1**	1.3/6	0.1/0.0	0.1/1	0.6/7	6
	2	1.2/6	0.3/0.0	0.2/2	0.7/8	6
	3	1.2/6	0.1/0.1	0.1/1	0.5/6	5
RS012	**1**	1.0/5	0.0/0.1	0.1/0	0.3/4	4
	2	1.3/6	0.0/0.0	0.0/0	0.3/4	4
	3	1.3/6	0.0/0.0	0.0/0	0.5/6	6
RS013	**1**	1.4/7	0.1/0.1	0.1/1	0.2/2	1
	2	1.4/7	0.0/0.1	0.1/1	0.2/2	1
	3	1.5/7	0.0/0.0	0.0/0	0.2/2	2
RS014	**1**	2.0/10	0.1/0.3	0.2/2	0.3/4	2
	2	2.2/11	0.1/0.4	0.3/3	0.5/6	3
	3	2.3/11	0.2/0.5	0.4/3	0.3/4	1

*measured to an assumed accuracy of 0.2 cm

RS009 and RS010 manipulated by rib lengths had negative lateral expansion across T, M, B and were therefore identified as non-auxetic through the constraints of the test. RS008 decreased at T and this was not within the 0.2 cm assumed accuracy in test 3 and therefore also appeared non-auxetic. The length displacement of the shoulder pads ranged between 3% to 11%, which was similar to the results recorded in Part 1. The difference between the percentage lateral expansion of the widest T, B and narrowest M widths (0% to 7%) were also within a similar range to Part 1. Therefore, manipulation of rib scale, anisotropy and cut widths did not significantly affect the opening consistency of the rotating squares structure at its width landmarks.

It was identified that increasing the cut widths of the internal structure in RS007 and RS008 led to lower tensile displacement compared to the original rotating squares structure, RS006. Manipulating the rib length of the internal structure to be shorter in RS009 as well as longer in RS010 also led to lower length displacement than the original, RS006. In test 1, no lateral displacement was recorded for RS007. In contrast, anisotropic shoulder pads generated 5% to 11% lateral displacement at L and 2% to 8% at the narrowest width M. However, mean lateral displacement at the widest widths was 0% to 3% for the anisotropic shoulder pads, which was lower.

Dimensional change at L was decreased by manipulating rib lengths of RS009 and RS010 and cut widths for RS007 and RS008 by approximately half. Manipulating the anisotropy of the rotating squares structure led to varied results. Vertical orientated rib lengths that were increased for RS011 and RS012 obtained approximately half the dimensional change at L compared to the original sample RS006. However, RS014 had horizontal orientated ribs, increased by 1.0 cm and gained similar tensile displacement to RS006. In summary, manipulating the rotating squares internal structure did not lead to an enhanced opening consistency and as such RS006 was the most consistent shoulder pad.

4.4.2.3 Pressure Comfort (Test 3)

Table 17 displayed the mean pressure comfort values recorded for the nine shoulder pads fitted to a mannequin. The results displayed the difference in pressure comfort between the front and back shoulder region across four arm positions. Patterns emerged for the three manipulation techniques which were compared to the original rotating squares structure, RS006. The ideal pressure comfort was defined as > 0 mmHg and < 3.2 mmHg, as used in Part 1.

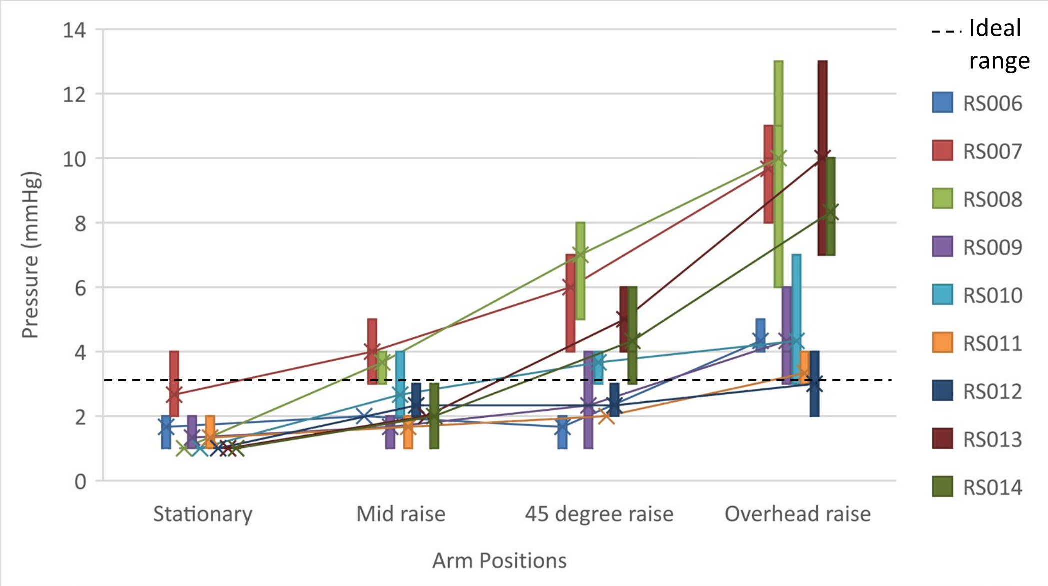
Table 17: Mean pressure comfort measurements of the nine pads

		The Four Arm Positions (mmHg)			
Pads	**Shoulder Region**	**Stationary**	**Mid**	**45 Degrees**	**Over Head**
RS006	Front	1.7	2.0	1.7	4.3
	Back	0.7	1.0	1.0	1.3
RS007	Front	2.7	4.0	6.0	9.7
	Back	1.7	2.3	4.3	7.0
RS008	Front	1.0	3.7	7.0	10.0
	Back	1.3	1.3	2.3	4.0
RS009	Front	1.3	1.7	2.3	4.3
	Back	1.0	1.3	1.7	2.3
RS010	Front	1.0	2.7	3.7	4.3
	Back	1.3	1.0	2.0	3.0
RS011	Front	1.3	1.7	2.0	3.3
	Back	0.0	1.0	2.0	2.3
RS012	Front	1.0	2.3	2.3	3.0
	Back	0.3	1.3	2.3	3.0
RS013	Front	1.0	2.0	5.0	10.0
	Back	0.7	1.0	2.3	4.0
RS014	Front	1.0	2.0	4.3	8.3
	Back	1.0	1.0	2.3	3.3

Table 17 documented that pressure comfort was within the range 1.0 – 10.0 mmHg for the front shoulder landmark across the nine pads, which was higher than Part 1. The range of results were smaller in the back for all nine pads, 0.0 – 7.0 mmHg. Shoulder padding with increased cut widths for example, RS007 and RS008 obtained the highest range in the back region. The results demonstrated that the greatest change in pressure between the four arm positions was to the front shoulder region, similar to the results presented in Part 1. In particular, the pressure comfort measurements obtained for the front shoulder region increased with the amount that the arms were raised as well as in the back-shoulder region. Therefore, pressure comfort increased as the shoulder padding became more convex in the 45 degree and overhead positions.

The original rotating squares shoulder pad RS006 obtained 0.7 – 1.3 mmHg in the back shoulder region, the smallest range of all nine pads, as displayed in the full set of results shown by the graph in Figure 71. RS006 obtained 1.7 – 4.3 mmHg in the front shoulder region across the four positions, the second lowest in the front, however it was above the ideal range. 0.3 – 3.0 mmHg was recorded for the front and back for RS012, it was the most suitable as the only pad within the ideal range. In general, pads with increased vertical orientated ribs, RS011 and RS012, obtained the lowest range of pressure comfort values in the front shoulder region and comparatively low in the back. Conversely, anisotropic shoulder pads with increased horizontal orientated ribs, RS013 and RS014, had the highest range of results in the front shoulder region, reflecting poor conformability.

a)



b)

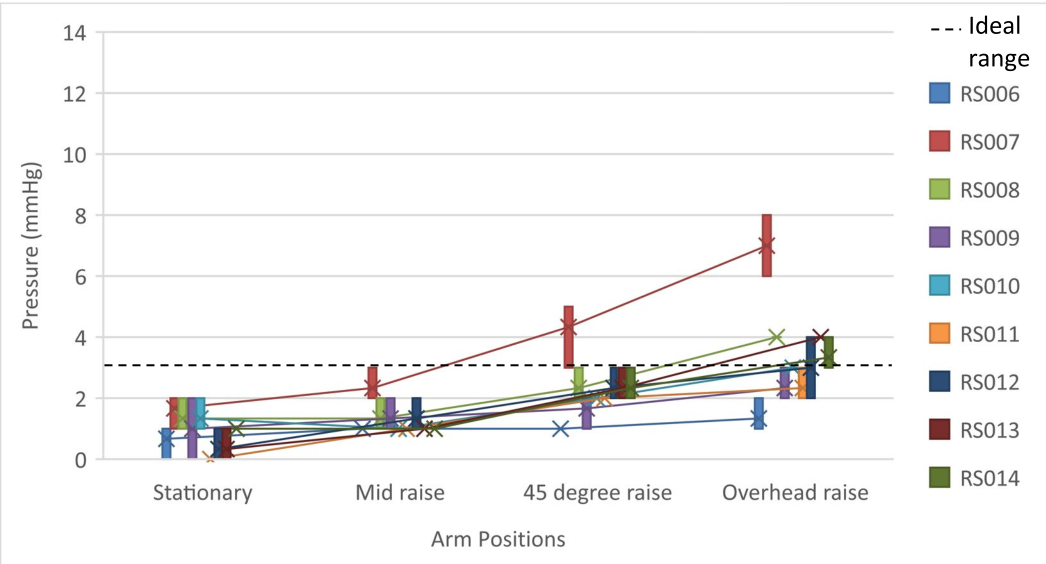


Figure 71: Mean pressure comfort measurements (mmHg) of nine shoulder pads at a) front and b) back shoulder landmark across four arm raises

In summary, compared to Part 1, the pressure comfort measurements were considered within the higher range across the nine shoulder pads. The original rotating squares shoulder pad had greater consistency in pressure comfort than shoulder pads manipulated with increased cut widths and anisotropic pads with increased horizontal orientated ribs. Therefore, shoulder pads with greater cut widths and increased horizontal ribs were identified as the least conformable pads in Part 2. The unmanipulated rotating squares structure led to a lower range than many of the shoulder pads and as such manipulation did not enhance conformability. However, it was identified that anisotropic rotating squares structure manipulated with lengthened vertical orientated ribs, RS012, had the greatest conformability of the shoulder pads.

4.4.2.4 Impact Tests (Test 4)

Nine shoulder pads were subject to impact tests over the flat, cylindrical and domed anvils. In Part 2 of the research, the results identified patterns in the peak forces obtained for shoulder pads with different manipulation techniques. The results in Table 18 display the peak forces obtained for the nine shoulder pads subjected to an impact energy of 5 J over three anvils. Shoulder pads that obtained low peak forces across the three anvils were thought to be the most suited to provide impact protection in shoulder padding. Tests were repeated three times and the mean was calculated as seen in Table 18.

Table 18: Peak forces (N) from impact tests of nine shoulder pads over three anvils

Shoulder Pads	Anvil	Test 1	Test 2	Test 3	Mean
RS006	Flat	2076	2104	2168	2116
	Cylindrical	3171	3875	4341	3795
	Domed	8459	8966	9094	8840
RS007	Flat	1970	2142	2152	2088
	Cylindrical	3070	3680	3727	3492
	Domed	8932	9448	9973	9451
RS008	Flat	2095	2115	2123	2111
	Cylindrical	3124	3744	3885	3584
	Domed	9382	9963	10086	9810
RS009	Flat	1906	1992	2056	1985
	Cylindrical	3042	3387	3485	3305
	Domed	7654	8730	9134	8506
RS010	Flat	1949	2028	2063	2014
	Cylindrical	2869	3255	3484	3203
	Domed	8150	9055	9487	8897
RS011	Flat	1961	1979	2058	1999
	Cylindrical	3014	3195	3356	3188
	Domed	8079	8855	9272	8735
RS012	Flat	1888	2004	2026	1973
	Cylindrical	2911	3225	3275	3137
	Domed	5337	8085	8835	7419
RS013	Flat	1931	2011	2051	1997
	Cylindrical	3100	3326	3465	3297
	Domed	7917	8796	9117	8610
RS014	Flat	1952	2033	2084	2023
	Cylindrical	2928	3248	3312	3162
	Domed	7451	8477	8636	8188

Impact tests on the flat anvil led to results within the range of 1973 – 2116 N, RS012 and RS006 had the lower and upper bound of the range respectively, as shown in Table 18. Over the cylindrical anvil, the range of mean peak forces were 3137 – 3795 N, RS012 and RS006 had the lower and upper bound of the range respectively, approximately double the range obtained over the flat anvil. Peak forces recorded from the domed anvil were within the range 7419 – 9810 N, RS012 and RS008 had the lower and upper bound of the range respectively, approximately triple those obtained from impacts over the flat anvil. Figure 72 demonstrated that increasing the anvil curvature led to an increase in peak forces, as the internal structures to opened out, also identified in Part 1. Mean peak forces in Part 2 were lower than those in Part 1 and the original structure in Part 2 obtained the highest peak forces over flat and cylindrical anvils. Therefore, lower peak forces were obtained for manipulated samples.

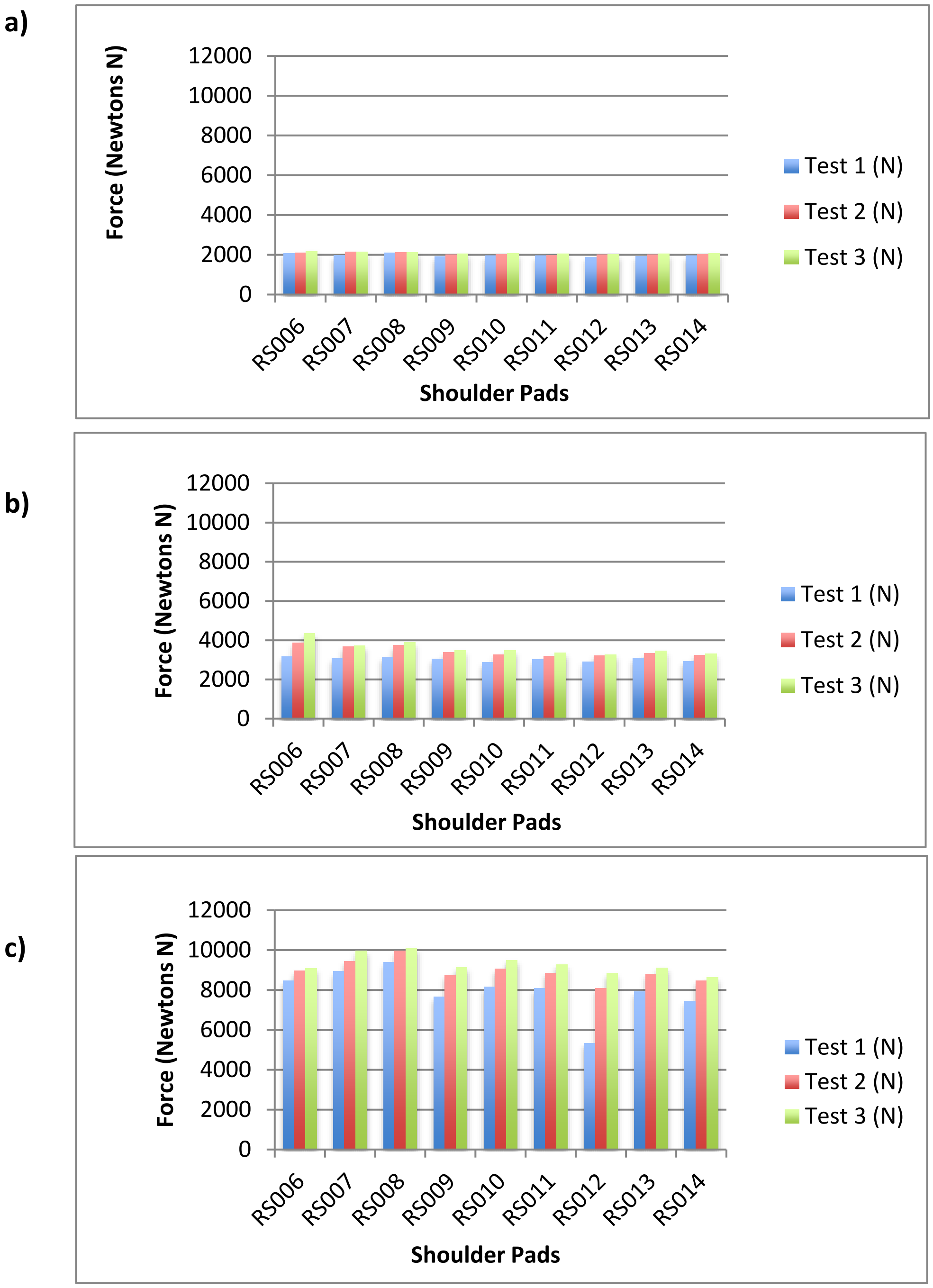


Figure 72: Forces (Newtons) from the impact tests of nine shoulder pads over three anvils; a) flat, b) cylindrical and c) domed

The highest peak forces were obtained for RS006 and shoulder pads with increased cut widths (RS007 and RS008), over the three anvils, which may have been caused by the increased width of material cut away from the pads. Whereas anisotropic shoulder pads, RS011 – 014 and shoulder pads with manipulated rib lengths RS009 and RS010 obtained the lowest peak forces over all three anvils. In particular, RS012 which had the greatest increase in vertical orientated ribs, obtained the lowest mean peak force over each anvil. However, peak forces may have differed depending on the positioning of the internal structure within the impact region, despite having the same over all pad position. Due to the differences in the manipulated internal structures, the individual unit cells of the pads may have been positioned differently under the impact striker, potentially affecting recorded peak forces.

In summary, in Part 2, the original rotating squares structure obtained higher peak forces than the manipulated shoulder pads, therefore manipulation enabled decreased peak forces. It was not surprising that shoulder pads with increased cut widths obtained higher peak forces under impact, having the largest segmented surface area before opening out. In contrast anisotropic manipulated variations enabled lower peak forces than the un-manipulated pad. RS012 obtained the lowest peak forces of all nine pads. Therefore, it was identified that anisotropic manipulation of vertically orientated ribs led to the best results for the shoulder pads.

4.4.2.5 Summary of Part 2

Rib lengths

In adjusting the rib lengths of the rotating square structure, RS009 and RS010 showed that conformability was not enhanced. The ribs of RS009 were shorter than the original and the ribs of RS010 were longer, yet no pattern emerged across the tests in increasing rib lengths of the structure. It was found that across the conformability tests RS009 and RS010 had a reduced opening consistency and lateral displacement compared to RS006, the non-manipulated rotating squares structure. Poor conformability was also indicated by the high range of pressure comfort values obtained for the shoulder pads. Finally, shoulder pads with increased rib lengths obtained higher peak forces than RS006.

Cut widths

The shoulder pads with increased cut widths had poorer conformability than the original structure, RS006. Through the tensile test, RS007 and RS008 had the second lowest tensile displacement and its opening mechanism was less consistent. The pressure comfort measurements of the two shoulder pads were in the highest range and as such by increasing the cut widths they were less conforming to body movements. It was shown that increasing cut widths for RS007 and RS008 resulted in increased peak forces across the three anvils. However, it was identified that increasing cut widths created a rectangular shape rather than the pointed ribs of the unit cells, this difference may have affected the conformability of the internal structure. Future investigations of cut widths should be conducted by increasing the diameter of the laser beam.

Anisotropy

Anisotropic shoulder pads obtained the lowest peak forces over the three anvils and as such performed better than the original RS006. Additionally, it was identified that RS011 and RS012, with increased vertically orientated ribs, had consistent pressure comfort and therefore were the most conforming. RS011 and RS012 also obtained high lateral displacement during the tensile and dimensional changes tests, obtaining the greatest opening inconsistency, with potentially less protective coverage. Shoulder pads with longer horizontally orientated ribs, RS013 and RS014 enabled lower lateral displacement but which was more consistent throughout the pad, and also achieved higher tensile displacement. The range of pressure comfort measurements were higher for RS013 and RS014 than those with manipulated vertically orientated ribs, as such were less conforming than the original.

Overall

Phase III presented that some auxetic structures can enhance the conformability of rugby shoulder padding without sacrificing protection. Manipulation of the rotating squares structure led to lower peak forces under impact, identified for anisotropic shoulder pads. All nine of the structures in Phase III led to increased conformability compared to the non-auxetic honeycomb shoulder pad in Part 1. However, the original rotating squares structure remained the most conformable shoulder pad in Phase III, Parts 1 and 2. The rotating squares structures with increased vertical orientated ribs were identified as the most suited to padding segmentation through the constraints of the tests in Phase III.

4.5 Summary of Chapter 4

This chapter presented the findings from Phases I to III. Phase I identified that discomfort prevented the majority of rugby playing respondents from wearing shoulder padding; wearer issues were identified across all six realms of comfort - thermal, weight, aesthetic, fit, sensorial and protection. Further analysis of the pressure comfort and fit of shoulder padding samples segmented three ways identified that none sat within the ideal pressure comfort range and most offered poor fit. Cut segmentation led to the greatest conformability and laser cutting also offered an effective route to producing auxetic patterns. Phases I and II identified that rugby shoulder padding discomfort was largely caused by poor pressure comfort and poor fit, which had not been evidenced in previous research.

The results presented in Parts 1 and 2 of Phase III determined that auxetic structures can be manipulated to offer rugby shoulder padding enhanced comfort benefits. Manipulation led to obtaining the ideal pressure comfort measurements defined for rugby shoulder padding in this research and auxetic structures led to generally greater conformability. However, some of the auxetic structures analysed in Phase III opened out less consistently and had potential to provide less protective coverage although compromises between fit and protection are common in sPPE development. Therefore, this research has identified that research recommending auxetic structures for protective body padding should take into account that synclastic curvature and biaxial expansion may affect protective coverage. There is need for the characterisation of a larger range of auxetic structures and manipulations, that further investigates impact testing in line with conformability.

5 Discussion

5.1 Introduction

This chapter critically discusses key findings from the literature review and results from phases I to III which met objectives 1 - 4. Key drivers for conducting this PhD were that sport personal protective equipment (sPPE) provides poor conformability and auxetic structures have the potential to offer an enhanced solution. sPPE is designed to protect against sport-specific injuries; however, it is thought that discomfort can reduce product use. The literature review, which fulfilled objective 1, showed that rugby sPPE materials offer poor conformability (Griffiths, 2009) and comfort (Finch et al., 2001). Webster and Roberts (2009) categorised comfort as six realms which are fit, protection, aesthetics, thermal, weight and sensorial. Therefore, to address the overall aim of the research which sought to identify the optimum parameters for the development of rugby shoulder padding that utilises auxetic PPE, this study was completed in three phases. Phase I quantified user perceptions and product use of commercial rugby shoulder padding, in response to objective 2. Phase II assessed product fit and pressure comfort to contextualise product performance with user perceptions, fulfilling objective 2. The final Phase (III) was designed to provide new insights into how auxetic structures can provide sPPE with enhanced conformability to the body in response to objectives 3 - 4. The key findings are synthesised to produce a recommended design process for rugby shoulder padding with auxetic elements offering enhanced conformability.

5.2 The Use of sPPE in Rugby

Rugby Union participants have a higher risk of injury than any other collision or impact sport (Moore et al., 2015), yet Phase I reported that 58% of respondents never wore rugby shoulder padding. sPPE is a non-mandatory element of player dress and it has not featured in World Rugby's (2018) 8-point plan to reduce injury which suggests that the use of sPPE in rugby is not considered critical to player safety. This may have contributed to the poor user uptake reported in Phase I as safety has been cited as the main reason for wearing rugby sPPE (Finch et al., 2001). This is further supported by the survey findings that 20% of respondents perceived that padding provided poor protective comfort. The same percentage felt that pads provided no protection against minor injuries soft tissue damage and lacerations, which padding is designed to protect against. In addition, players of all training levels were discouraged from wearing rugby shoulder padding by coaches and teammates. Discouragement was most significant for professional players. According to World Rugby (2019a) only at a professional training level must medics be present during participation as such lower training levels may feel that rugby shoulder padding is more critical to injury reduction. Therefore, it is likely that low beliefs in the protectiveness of padding may be one of the causes for its poor user uptake.

Shoulder Injury

The shoulder is at highest risk of injury from Rugby Union tasks and movements (Funk, 2012), especially the tackle (Swain et al., 2016). Surprisingly, two thirds of survey respondents never used rugby shoulder padding and tackle exposure of player positions was not found to affect product use. Furthermore, 20% less respondents wore rugby shoulder padding than those that believed in its protective function against minor injuries. This was striking given that perceived protection was found to be the most important realm of comfort in the study. However, approximately half the survey respondents were aware that shoulder padding would not protect them against major injuries, such as dislocation and breakage, similar to the number of respondents that did not wear padding. The findings implied that if padding provided protection against major injuries it would have potential to encourage product uptake due to the high risk of shoulder injury and criticality of protection to perceived user comfort.

Social Influence

Family were the only external influencers of rugby shoulder padding use in comparison, to coaches and teammates, on the rugby pitch. The discomfort of wearing rugby shoulder padding reported by players may explain the discouragement between rugby peers. As Kerr (2018) and Morrell (2017) explain rugby is regarded as an aggressive sport with traditional sporting values (Morrell, 2017; Kerr, 2019). Therefore, it was possible that discouragement stemmed from preserving the nature of the contact sport. Whereas, family may have been more likely to encourage product use due to their external position as observers of the sport and its associated risks.

Even though Finch et al., (2001) reported that the appearance of rugby sPPE was its most important design feature to players, aesthetic comfort was perceived unsatisfactorily by the majority of survey respondents in Phase I. The poor conformability of commercial pads analysed in Phase II lifted and bunched, causing bulkiness which is considered detrimental to the appearance of PPE (Dabolina and Lapkovska, 2020). Recreational level players reported the least satisfaction with aesthetic comfort and yet were least likely to be taught strategies for effective technique and injury reduction (Hendricks and Lambert, 2010) or receive medical attention on the pitch (World Rugby, 2019a). Survey findings showed that aesthetics were least likely to influence the purchase of rugby shoulder padding yet were influenced by fit problems, which were most likely to prevent a purchase. Poor aesthetic comfort has been shown to decrease self confidence in social environments including rugby (Russell, 2004) and as such it was likely that aesthetic comfort would influence product use amongst rugby peers.

5.3 World Rugby Regulations (WRR)

The World Rugby (2019b) Body Padding Specification advises that shoulder pads should not hinder or cause discomfort to normal player movements. In Phase II, the nine commercial pads obtained poor and inconsistent pressure comfort between four active positions and poor pressure comfort can restrict mobility and comfort including fit (Webster and Roberts, 2009). Fit comfort of padding was identified as unsatisfactory to survey respondents in Phase I. Therefore, the findings from Phases I and II confirmed the association between poor pressure comfort and fit comfort of rugby shoulder padding with likelihood to interfere with normal player movements. Sections below discuss the World Rugby (2019b) Body Padding Specification in respect to the conformability and fit issues identified for commercial pads in Phase II.

Homogeneity

The World Rugby (2019b) Body Padding Specification shoulder pads must be homogenous such that internal and external faces are of the same texture, density and hardness, with no rigid projections. However, Phase II showed that the internal and external faces of vacuum moulded commercial pads did not have a homogenous texture. This was because the segments protruded on the external but not the internal face, exhibiting a different feel and appearance. In addition, the segments of Gilbert Triflex V3 commercial pads were finished with a harder shell on the external face, whereas the internal face was finished with a fabric of nylon and elastane composition. Therefore, the product user would have been exposed to a softer texture on the internal face compared to the external which faced the opponent. The four vacuum moulded commercial pads bunched, also generating poorer pressure comfort than the three cut-segmented pads considered to have homogenous texture, density and hardness. Where vacuum moulded segments bunched it was likely that the bulk of protective closed cell foam also increased. Pad bulkiness is associated with weight (Hur et al., 2013) which can cause discomfort (Park et al., 2014), this research showed that pad bulkiness provided poor weight comfort because it received the lowest satisfaction in the Phase I survey. Therefore, the bunching and poor fit caused by the non-homogeneity of vacuum moulded commercial pads were likely to provide discomfort that could disrupt normal player movements.

Zone of Coverage

The World Rugby (2019b) Body Padding Specification stipulate that the maximum zone of coverage extends between the sternoclavicular, acromioclavicular and glenohumeral joints. In Phase II, the nine commercial pads varied in shoulder position within the maximum zone of coverage. Of the assessed pads, the largest design (Body Armour Flexitop BA) led to poorer conformability. Commercial pads designed to extend over the top of the shoulder also provided poor conformability. Vacuum moulded pads led to bunching and remaining commercial pad types lifted away. However, Beer and Bhatia (2009) have reported soft tissue bruising of the trapezius, the deltoid, the pectoralis major muscles and those surrounding the shoulder which extend beyond the maximum zone of coverage. This implies that the current zone of coverage is not sufficient and 40% of survey respondents felt that wearing rugby shoulder padding did not improve their perceived protective comfort. Therefore, the maximum zone of protective coverage should be increased but improving conformability of the pads is critical to increasing protective coverage.

None of the Phase II commercial pads utilised the maximum dimensions of the zone of coverage (World Rugby, 2019b). The commercial pads were designed in a variety of sizes and a 40% difference was identified between the largest (Body Armour Flexitop BA) which was 82.1 cm and 59.5 cm, the smallest (Canterbury Vapodri Raze). However, commercial pads with smaller circumferences generally displayed greater conformability compared to those with larger circumferences of the same segmentation type. Fit and protection were the most critical comfort realms to survey respondents yet increasing protective coverage was a compromise found to reduce conformability and quality of fit, proving that the two remain trade-offs in the development of auxetic sPPE. Pain et al., (2008) identified that the acromioclavicular joint was the only region of the shoulder subject to force reduction during the front on tackle. Their findings implied that positioning and size of padding were likely to influence location of force reduction, yet Body Padding Performance Specification (World Rugby, 2019b) does not stipulate critical shoulder protective regions.

5.4 Conformability of Commercial and Auxetic Rugby Shoulder Pads

In Phases II and III, commercial and auxetic rugby shoulder pads differed by segment unit cell scale and shape. In Phase III, the auxetic pads were cut-segmented whereas commercial pads in Phase II included non-segmented and vacuum moulded variations too. In Phase II, the unit cell shapes used to segment commercial pads included triangular and hexagonal geometries and were subject to fit assessments as well as pressure comfort analysis. In Phase III part 1, five auxetic pads were developed with identical outer dimensions but segmented with different unit cell shapes. The five auxetic pads were subject to tests of tensile displacement and dimensional change, pressure comfort assessments and impact tests over curved and flat anvils to show the effect of synclastic curvature on impact protection. This section discusses the extent to which auxetic internal structures offered an enhancement to the coverage and conformability of rugby shoulder padding.

Unit Cell Shape

In Phases II and III both commercial and auxetic pads varied by unit cells in triangular, hexagonal and quadrilateral shapes. The variety of unit cell shapes has been applied to other types of sPPE including helmet linings (Gooding, 1981; Caserta et al., 2011), back protectors (Boria, 2016) and general protective athletic garments (Diamond, 2013; Brandt, 2018). According to Sun et al., (2012) and Harris and Spears (2010) the effect of unit cell shape has not been assessed in relation to the performance of sPPE. In this study, results of Phases II and III indicated that unit cell shape can affect conformability and fit which in turn affects protection (Cubeddu, 2016). Another important finding was that auxetic unit cells provided enhanced conformability and protective coverage when the opening mechanism was consistent throughout the auxetic pad.

Triangular Unit Cells

The triangular unit cells in Phases II and III were equilateral; a characteristic of this shape is its foldability enabling its use for collapsible PPE (Avelino and Santos, 2012). However, the bunching of triangular vacuum moulded commercial pads in Phase II was likely to be caused by the folding of triangles when fitted to the curvature of the shoulder. In addition, triangular unit cells obtained high pressure that was outside of the ideal range and may have been detrimental to perceived sensorial comfort (Sweeney and Branson, 1990). In Phase III, the auxetic pad with triangular chiral structure also had an inconsistent opening mechanism. However, auxetic triangular structures opened out and due to this difference were unlikely to fold in Phase III and folding was not observed, suggesting that the fit problems were different. Auxetic structures comprised of rotating units are typically stiffer than unit cells separated by ligaments (Mizzi et al., 2020) due to more than one cut line, such as the triangular chiral structure. Therefore, it is possible that auxetic structures with ligaments have a less consistent opening mechanism than rotating units such as the rotating squares structure.

Quadrilateral Unit Cells

Phase III four-sided unit cells included rotating squares and 4-pointed star; the former offered greater opening consistency and pressure comfort. Whereas, the unit cells of the latter did not open out symmetrically, instead the unit cells slid against one another, which is known as shearing (Lipton et al., 2018). The rotating squares structure comprised of one repeated cut in vertical and horizontal orientations whereas 4-pointed star had two perpendicular overlapping cuts at a 45-degree orientation. Shearing is undesirable for sPPE (Yang et al., 2015) and is considered to have a negative effect on tactile comfort (Kar et al., 2006) also known as sensorial comfort (Das and Ishtiaque, 2004; Bensaid et al., 2006; Kayseri et al., 2012). These results are consistent with the survey data where padding offered respondents poor sensorial comfort, and therefore it was likely that the shearing effect of 4-pointed star could cause poor sensorial comfort. The 4-pointed star was connected by ligaments which have been shown to have increased stiffness compared to rotating units (Mizzi et al., 2020), hence may explain the improved conformability of the rotating squares structure.

Hexagonal Unit Cells (Honeycomb Structure)

Of the hexagonal, six-sided shapes in Phase III, 3-pointed star led to the lowest peak forces over the flat anvil, whereas non-auxetic honeycomb recorded the lowest values over curved anvils. One hexagon comprises of six equilateral triangles (Govindaraj and Sudhakar, 2018), as such where hexagonal and triangular unit cells have the same length sides, the former benefits from a surface area that is six times larger. Therefore, it is possible that larger unit cells led to lower peak forces under impact. In addition, Phase II fit analysis results indicated that commercial hexagonal shapes enabled better positioning and fit within the protective region than triangular. However, auxetic triangular shape, 3-pointed star, had an inconsistent opening mechanism, which was thought to cause the structure to lead to higher peak forces over curved anvils compared to quadrilateral shape rotating squares. A possible explanation might be that increasing the number of intersecting cut lines decreased the control and consistency of the opening mechanism. It is possible, therefore that consistency of opening mechanisms affected the fit and protective function (Cubeddu, 2016) of the auxetic pads and in turn the perceived comfort of survey respondents.

In general, the honeycomb structures enabled greater pressure comfort but only the non-auxetic alternative led to enhanced conformability than other assessed shapes.

In particular, commercial honeycomb pad Canterbury Vapodri Raze Pro was comprised of one repeated cut which offered enhanced conformability and pressure comfort compared to the remaining commercial pads. Therefore, it was possible that reducing the number of intersecting cuts improved conformability, as observed for triangular and quadrilateral unit cells too. There was also evidence to suggest that the unit cell had auxetic elements due to its geometry. In which case, the honeycomb structure may have provided enhanced conformability due to its possible auxetic elements in an arrangement of singular cuts.

Segmentation Type

In Phase II, unit cells of the same shape which utilised different segmentation methods produced varying fit and pressure comfort results; the reason for this appeared two-fold. Firstly, when comparing tops of same brand that featured the different segmentation types, fit assessments on the same model showed variance in garment dimensions of the XL tops. A general observed pattern was that vacuum moulded tops had a looser fit, despite brands offering a universal size guide across the commercial shoulder pads, which was the case for the assessed Gilbert and Canterbury tops. The looseness led to poor pressure comfort where 0 mmHg was recorded for many active positions in Canterbury and Gilbert vacuum moulded tops. In contrast, the vacuum moulded Kooga IPS V was the only top of that brand assessed but had the smallest dimensions of all vacuum moulded tops, resulting in the tightest fit which led to the highest-pressure levels recorded in Phase II. Therefore, it’s possible that Gilbert and Canterbury produced tops featuring cut-segmented pads in smaller dimensions and tighter fit, due to the greater conformability that this segmentation method enabled. It was not possible to compare with the auxetic pads in Phase III as they were all cut-segmented and individually embedded within the pocketed region of the same top. However, with future developments of through-the-thickness auxetic closed cell foam (Fan et al., 2018) for sPPE it is likely that cut segmenting may also lead to enhanced conformability compared to vacuum moulding.

5.5 Rugby Shoulder Padding with Manipulated Auxetic Internal Structures

Phase II and Phase III part 1 showed that conformability was affected by segmentation type and unit cell shape. In the next Phase (III part 2) nine auxetic pads were cut-segmented with the same auxetic shape manipulated by rib lengths, cut widths and anisotropy. This phase focused on the rotating squares structure, identified as more conformable to the shoulder region than remaining shapes in part 1. The results showed that anisotropic variations offered good conformability and lower peak forces but the unmanipulated version remained the most conformable. Therefore, it would have been interesting to explore manipulation of other shapes from Phase III part 1 to see if manipulation effects were dependent on shape.

Rib Lengths

In both Phases II and III, internal structures with 1.0 cm rib lengths had greatest conformability to the shoulder region. Therefore, the rotating squares structures manipulated with 0.5 cm and 1.5 cm rib lengths in Phase III part 2 did not enhance conformability to the shoulder region. However, the shortest rib lengths (0.5 cm) opened out such that its' cuts became circular like the auxetic perforated sheet (Taylor et al., 2013) rather than a rotating squares structure (Grima and Evans, 2000). The resulting effect was that the unit cells comprised of 0.5 cm rib lengths enabled less expansion. Prawoto (2012) has shown that structures with smaller opening typically have a smaller negative Poisson's ratio. Therefore, manipulation of rib lengths resulted in a change of the opening mechanism and possibly its Poisson's ratio, but it was likely that this was because the ribs remained the same distance apart.

Cut Widths

In Phase III part 2 unit cells with increased cut widths provided poorer conformability and protective coverage compared to the unmanipulated version with 0.1 cm cut widths. The opposite effect was identified for non-auxetic unit cells. In Phase II, Body Armour Flexitop BA had 0.1 cm cut widths, the narrowest of the honeycomb, cut-segmented commercial pads. The top did not conform well to the shoulder, generating poor pressure comfort recorded as 0 mmHg which was also evident as the commercial pads lifted away from the shoulder. The majority of survey respondents reported low satisfaction for fit comfort and yet this is critical to its protective function (Cubeddu, 2016). Therefore, the effect of pads lifting away from the shoulder was likely to have also caused the commercial pads to move from the intended protective region. The difference in effect of cut widths was that only the auxetic structures were able to open out due to biaxially expanding under tension (Martin, 2011; Cross et al., 2015). In this assessment, the effect of space between segments differed between auxetic and non-auxetic unit cells.

Anisotropy

The unmanipulated rotating squares structure led to enhanced conformability but second to this were structures manipulated with anisotropic geometry. In Phase III part 2, auxetic pads with increased horizontally orientated ribs had greater tensile displacement before failure whereas increased vertically orientated ribs led to greater lateral expansion. Mizzi et al., (2020) showed that in plane rotating squares structures with increased rib lengths in the vertical orientation (anisotropic) enabled higher Negative Poisson’s ratio at the central unit cell compared with ribs of the same length (isotropic). However, the anisotropic samples were subject to greater deformation at the centre of the sample than the isotropic version (Mizzi et al., 2020). Phase III part 2 found similar results with greater deformation at the centre causing poorer consistency of the overall opening mechanism. Greater opening at the centre may have in part been due to the figure 8 shape of the auxetic pads but also because the centre of the auxetic pads were less constrained by the end clamps in the tensile test (Mizzi et al., 2020). Gilbert Triflex V3 which was also comprised of 2.0 cm rib lengths, the largest of the commercial pads provided poorer pressure comfort and conformability to the shoulder region of the commercial pads in Phase II. Therefore, it is possible that higher negative Poisson's ratio causes a more inconsistent opening mechanism and poorer conformability but the increased scale may have also been a factor.

In Phase III part 2 the anisotropic samples led to lower peak forces than the unmanipulated rotating squares structure subject to impact tests. This finding was interesting given that the anisotropic samples in this research and that by Mizzi et al., (2020) had opening mechanisms subject to greatest deformation at the centre. Therefore, the auxetic pads were likely to be more exposed at central regions. However, given that the anisotropic samples had increased rib lengths they would have provided a larger surface of protective coverage per segment which may have led to lower peak forces during impact tests. Therefore, it was unlikely that the anisotropic geometry led to lower peak forces specifically but rather the increased surface area of unit cells this led to.

5.6 Summary of the Key Findings of the PhD

This research has shown that proper fit of sPPE is critical to function, both to encourage product use and preventing movement from the body region under protection. Phases II and III confirmed the association between pressure comfort and fit of sPPE, showing a need to offer greater conformability and pressure comfort as a means of encouraging user uptake. Therefore, the findings suggest potential discrepancy between the World Rugby (2019b) Body Padding Specification and commercial rugby shoulder pads. It seems that designing padding in accordance with the regulations more rigorously could improve fit and that the protective zone of coverage could even be expanded. However, padding was not considered critical to player safety and user uptake may be encouraged if these protective materials mitigated higher risk injuries. Therefore, discouragement from sPPE use was central to the game and sporting participants and future designs should look to improve their comfort perceptions across fit, protection, sensorial, aesthetic, weight and thermal comfort.

The research conducted through this PhD has shown that auxetic structures can provide sPPE with greater conformability to the body depending on unit cell geometry. It was discovered that the opening mechanism of auxetic structures influenced conformability and protective coverage. An opening mechanism that is consistent throughout the structure is desirable for sPPE to prevent cut-segmentation from opening larger at regions, exposing the body. Auxetic unit cells separated by ligaments have a less consistent opening mechanism than rotating units such as the rotating squares structure and previous research has suggested that the former is stiffer which may explain the effect. However, where unit cells were separated by ligaments a lower number of intersecting cuts was desirable. Manipulating the auxetic rotating squares structure showed that tailoring its geometry could affect its performance. There were limitations to the assessment of manipulation in this research, for example to further investigate the effect of scale through manipulating rib lengths, the space between rib lengths should be adapted accordingly.

5.7 Developing sPPE with Auxetic Structures

sPPE design has a focus on the unique injury patterns and athletic demands of a specific sport and body region. The strategy for developing, assessing and implementing rugby shoulder padding with auxetic structures can also be applied to other types of sPPE. Impact tests over flat and curved surfaces showed that previous claims of auxetic structures could offer sPPE greater conformability were not universal due to the respective opening mechanisms of different auxetic unit cells. Opening consistency was identified as the leading factor in protective coverage and conformability of auxetic structures. Hence, the effect of unit cell geometry is critical in designing sPPE with auxetic structures.

It was identified that a strategy for developing conformable sPPE could be adapted from user-centred design frameworks used for PPE in healthcare (Larson and Liverman, 2011) and functional clothing (Watkins and Dunne, 2015). Both have similarity where the first stage involves determination of the problem through user requirements and product analysis to determine the barriers to PPE use. Following this, the second stage ideates design solutions, having identified key characteristics for development. Then the third stage implements and evaluates findings to inform realistic consequences of use. Applying the research outcomes to the format of pre-existing user-centred design frameworks was determined the best route to providing designers a strategy for implementing auxetic structures within padding and in turn, improving product uptake. Section 5.7.1 maps out the findings of this research against the strategy for developing sPPE with auxetic structures shown in Figure 73.

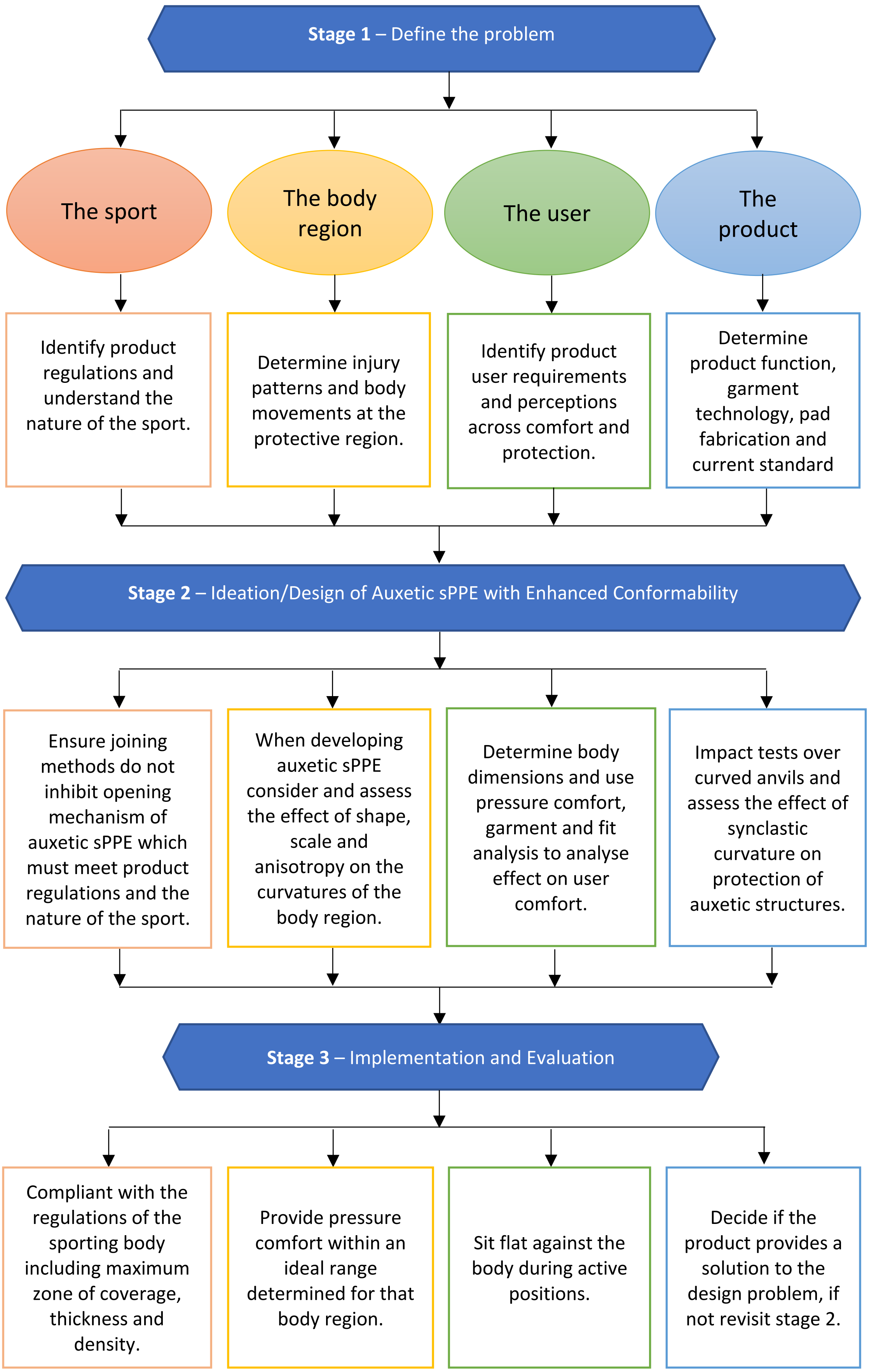


Figure 73: Recommended strategy for developing sPPE with auxetic structures

5.7.1 Recommended Strategy for Developing Rugby Shoulder Padding with Enhanced Conformability

This PhD investigated whether auxetic structures pose as an enhanced solution to current commercially available rugby shoulder padding. Through this process key findings have arisen with potential to inform pad designers, auxetic research of sPPE and the World Rugby (2019b) Body Padding Specification. The following sections expand on the strategy for developing sPPE with auxetic structures displayed in Figure 73 in respect to rugby shoulder padding, which is the focus of this research.

The Sport – Rugby

This PhD has identified that the World Rugby (2019b) Body Padding Specification definition of homogeneity, in which two pad faces must comprise of the same texture, hardness and density, should be extended to include pad surface consistency. Surface consistency extends to pads segmented with non-auxetic and auxetic shapes as the inconsistent surface of vacuum moulded commercial pads comprised of low and high points that enabled segments to bunch and fold. Auxetic shapes arranged by singular cut lines led to greater opening consistency and lower peak forces over curved anvils and therefore were most suitable for segmenting sPPE. However, the unit cells of auxetic shapes that did not have this geometry opened out wider at different regions; this effect was likely to cause higher exposure to rugby injury. Therefore, opening consistency and surface consistency of pads provide good fit and impact tests over anvils of a range of surfaces, including domed, proved to be a useful method of measuring the effect of opening consistency on peak forces. At present, the World Rugby (2019b) Body Padding Specification hammer and anvil test is conducted using a cylindrical anvil and therefore neglects the effects of domed curvature on protection, such as at the top of the shoulder. Future developments of anvils with realistic body region curvatures and stiffness will enable pad developers to adopt realistic impact tests for different types of sPPE.

The pad segmented with rotating squares structure was formed by an arrangement of singular cut lines; it conformed well to the shoulder and provided the ideal pressure comfort range between active positions. The pressure comfort and fit provided by this structure was thought to minimise disruption to player movement and comfort, criteria of the World Rugby (2019b) Body Padding Specification. Therefore, the rotating squares structure and potentially other auxetic shapes in an arrangement of singular cut lines are recommended for the segmentation of rugby shoulder padding. An ideal pressure comfort range was defined for this research and active positions were identified for rugby shoulder padding. The ideal pressure comfort range proved to correspond to pads with consistent opening mechanisms and proved that defining ideal pressure comfort ranges for different sPPE can quantify the effect of fit on user comfort.

None of the commercial pads assessed in this research utilised the World Rugby (2019b) Body Padding Specification maximum zone of protective coverage yet protective comfort was the most important realm of comfort to survey respondents and product uptake was low. Larger commercial pads provided the worst fit in this study, such as bunching and lifting, it was likely that full use of the maximum zone of coverage for commercial pads would have exasperated these issues. However protective coverage should be maximised; force reduction has been identified at central regions rather than throughout pads and soft tissue damage and lacerations to the shoulder have been reported beyond the maximum zone of coverage. This research identified that cut-segmented auxetic pads conformed well to the shoulder region and provided the ideal pressure comfort range due to laterally expanding under tension. Therefore, if the World Rugby (2019b) Body Padding Specification increased the maximum zone of coverage beyond the trapezius, deltoid, pectoralis major muscles and pad designers utilised cut-segmented auxetic structures, auxetic pads could offer increased protective coverage and enhanced fit.

The Body Region - Shoulder

Commercial pads which extended over the top of the shoulder were subject to the greatest fit issues. This was due to the steep curvature of the top of shoulder and the poor conformability of the pads which led to lifting away from the shoulder, potentially causing less protective coverage. Anisotropic auxetic pads showed the ability to control extension in specific directions and in turn minimised opening out of the structure and exposure to impacts. Anisotropic auxetic pads benefit from the ability to restrict extension in one direction and maximise extension in the perpendicular. Where pads are designed to extend over the top of the shoulder the anisotropic rotating squares structure with longer vertically orientated ribs are recommended to enable increased pad extension across the horizontal plane of the body.

Auxetic pads were shown to conform well to the shoulder and led to the ideal pressure comfort range. However, compared to the non-auxetic pad, with increased curvature, auxetic pads led to higher peak forces, likely caused by the ability to laterally expand. In contrast, auxetic rotating squares structure manipulated with shorter ribs but original spacing restricted the ability to open out compared to the remaining auxetic pads. It was identified that opening out was not restricted because the ribs were shorter specifically, instead the subsequent increased difference between rib length and separation between ribs led to decreased opening of the unit cell. This research found that 1.0 cm rib lengths led to the greatest conformability, but it is advised to decrease ribs to 0.5 cm at the top of the shoulder, in order to increase the difference between rib lengths and separation between them. This application has potential to decrease opening of the structure and prevent higher exposure to injury at the top of the shoulder where the curvature is steepest and most likely to open out greater.

The User – Rugby Players

Fewer than half the respondents wore padding, similar findings were obtained twenty years ago (Finch et al., 2001). The main reason for poor uptake was unsatisfactory comfort requirements, especially perceived weight comfort which was related to bulkiness. Fit assessments of commercial tops showed that bulkiness was exasperated by segment bunching of vacuum moulded pads as well as non-segmented and cut-segmented padding that lifted away from the shoulder. Therefore, this research showed that perceived weight discomfort was likely to be exasperated by poor conformability of padding. In contrast, all of the developed auxetic pads sat flat against the body and enabled good pressure comfort, whilst rotating squares structure enabled consistent opening out. Therefore, to improve user uptake of padding, padding designers are advised to maximise the zone of coverage and segment with auxetic structures arranged in singular cut lines to improve comfort.

The Product – Rugby Shoulder Padding

This research found that cut-segmented auxetic structures provided an enhanced solution to the poor conformability of commercial rugby shoulder padding. Vacuum moulded pads caused poor conformability and fit issues, partly due to the rigidity of pads that were stitched in place and bonded, disabling the stretch of the top. Cut-segmented commercial pads were pocketed rather than stitched in place, preventing restriction and enabling greater flexibility and fit than vacuum moulded alternatives, as were the cut-segmented auxetic structures in this study. Breaking point for all auxetic pads under tensile displacement was 31 to 59% and body movements may extend the body's skin by about 50% which stretch sportswear is designed to accommodate. Embedding methods must enable pads to freely expand upon conforming to shoulder curvatures and movements such as through pocketed padding. In contrast, using embedding methods that attach pads to the stretch garments with elastane content could cause the opening mechanism to over-extend and open out rather than conform freely.

Padding is designed to protect against soft tissue damage and lacerations, but it was identified that if pads provided protection against more severe injuries, dislocation and breakage then product uptake could be improved. Of the assessed commercial pads, cut-segmented offered the best conformability and fit but all led to lifting or movement of the padding from the protective region. In addition, all the size XL participants had individual body types affecting the position of the pads within the shoulder region. Therefore, limiting smaller protective regions further as they may not be positioned accordingly on individual product users. This research has shown that auxetic structures can improve conformability to the shoulder region, enabling the use of larger pads.

5.7.2 User-Centred Design

User-centred design methodologies were not applied to this research which utilised quantitative test methods to evaluate rugby shoulder padding, product perceptions and alternatives segmented with pre-existing auxetic geometries. The strategy outlined in Figure 73 was adapted from pre-existing user-centred design frameworks. The strategy could be expanded or tailored by designers utilising user-centred design methodologies to incorporate user-feedback at each of the three stages. Fit assessments could be added to the Body-region column, wearer trials to the Product column and interview feedback to the User column, delivering valuable user-feedback to the development process. The strategy will provide pad designers utilising user-centred design methodologies an iterative path to follow and tailor to their requirements in the development of sPPE with auxetic structures.

Stage 1 - Define the Problem

This research used quantitative research methods to define the problem with current rugby shoulder padding. In contrast, qualitative methods such as interviews or a survey devised of open-ended questions would have been critical to framing the user's needs in a user-centred design approach, extracting unpredicted information (Busetto et al., 2020). Observation was used at the start of Phase II to document garment appearance, fit and construction, an important tool in a user-centred design strategy (Ledbury, 2018). However, Phase II was adapted in place of quantitative methods considered more suitable for this research, due to the difficulty interpreting qualitative data (Fink, 2015). Documenting garment appearance could be useful to take forward in future research applying auxetic structures to sPPE and could be incorporated within the initial stage of the strategy shown in Figure 73.

Stage 2 - Ideation/Design

At the second stage of this research, ideation focused on tailoring auxetic geometrical arrangements. Differences in geometry were investigated in relation to effects on conformability and peak forces, excluding the user from this stage. However, for a user-centred design approach, users could have been incorporated into the pressure comfort assessments, which could be adapted in the development strategy outlined in Figure 73. User-centred design strategies might have also considered focus groups as part of this stage, to generate user-ideation that would inform design (Ledbury, 2018). The strategy outlined in Figure 73 could be developed such that at Stage 2 each of the four columns are adapted to include idea generation focus groups and human interaction.

Stage 3 – Implementation and Evaluation

At the final stage, pads were implemented by insertion within the pocketed shoulder region of a rugby top and evaluated through physical tests that excluded user interaction. A user-centred design approach considers wearer trials to offer the most comprehensive evaluation of the user's experience in the garment (Watkins, 1995). However, this research investigated padding conformability rather than the padded garment in its entirety. Researchers using the development strategy (Figure 73) for applying auxetic structures in sPPE could integrate wearer trials into the final stage to evaluate the garment through the user. This information is valuable to the pad designer to determine human experience and is not possible to predict on a mannequin.

5.8 Wider Applications

Through this research key findings have arisen relating to the wider fields of sportswear, PPE and auxetic research generally. Recently, auxetic shapes have been explored in respect to structural response to deformation (Mizzi et al., 2020), but not in relation to consistency of the opening mechanism. The research findings that opening mechanisms of different auxetic structures are of varying consistency could be of benefit to medical applications. This characteristic could enable localised lateral expansion for example in a stent or a bandage delivering pain relief where swelling is focused. In sportswear, structures offering an inconsistent opening mechanism may also be of benefit where localised expansion is required for tailored fit such as in footwear.

This research has shown that pressure comfort assessments can quantify rugby shoulder padding fit issues. This method could be applied across performance assessments of other types of sPPE in the sportswear industry as well as academic research to identify the effect of padding bulkiness on fit as well as user comfort. In general comfort is neglected in sporting body regulations for performance assessments of respective sPPE. It has been previously commented that sPPE fit is critical to function and that discomfort is a leading deterrent from product uptake. Therefore, where sporting bodies stipulate that sPPE must not hinder comfort or movement, the regulations should stipulate performance assessments that address this.

The findings regarding manipulating auxetic geometry to produce different opening mechanisms will be informative across the development of auxetic sPPE for other sports and body regions. Auxetic structures comprised of a lower number of intersecting cut lines, such as rotating squares, offered a more consistent opening mechanism. The rotating squares structure has suitability to padding at body regions subject to multiple directions of movement to prevent restriction of movement. This includes the shoulder and is not limited to rugby, with suitability to shoulder padding comprised of closed cell foam worn for other collision sports including lacrosse. Cut-segmentation that provides a consistent opening mechanism ensures protective coverage is in turn consistent throughout the pad.

This research found that PPE with auxetic segmentation comprising of thinner cut widths minimised the trade-off between fit and protection of padding, the thinnest evaluated in this research was 0.1 cm. In contrast, increased cut widths led to higher peak forces, 0.4 cm was the largest applied to padding in this research. Auxetic structures enable biaxial expansion that conforms to body movements and facilitates stretching of the skins surface. However, larger opened out regions also decrease protective coverage and as such larger cut widths are more suited to PPE facilitating concave or closing movement including shock-absorbing padding at the palm of a glove. Auxetic structures with a high number of intersecting cut lines would be most suited to this PPE application too, such as the 4-pointed star. Of the evaluated structures, the 4-pointed star had the least consistent opening mechanism and conversely could lead to biaxial contraction at regions under higher strain such as the centre of the palm when the hand is in a closed or fist position.

Tailoring auxetic structures by decreasing the rib length ratio compared to length between cut lines led to restriction of the pad's opening mechanism. sPPE with critical zones of coverage would benefit from restricting the opening mechanism at specific regions of the pad. Restricting the opening mechanism of padding at regions subject to both higher occurrence of injury and strain due to movement could ensure greater protective coverage. For example, a volleyball elbow or knee pad with auxetic segmentation may open out greater at its centre during flexion which could in turn decrease protective coverage at that region during a fall in which the player lands on a flexed arm or a bent knee. Tailoring the ratio of rib lengths to lengths between cut lines at the region under highest strain has potential to restrict the opening mechanism at that region to maximise protective coverage. Anisotropic auxetic segmentation is also recommended to restrict the expansion of padding subject to only one direction of movement, such as knee pads, due to the ability to restrict expansion in the perpendicular to the direction of movement in the knee.

5.9 Discussion Chapter Summary

This chapter synthesised key findings from the preceding phases. Synthesis was chronological, occurring first through the commercial product and product users and then integrated with findings from developing auxetic structures as an alternative solution. Through this process it has been possible to make recommendations for the use of auxetic structures in sPPE. Limitations of this process have also opened further lines of enquiry that should be addressed in future research. Therefore, the outcome recommends direct applications for the use of auxetic structures in sPPE and rugby shoulder padding as well as parameters for consideration in its further development.

6 Conclusions and Recommendations

6.1 Introduction

Since the commencement of this PhD, research and applications of auxetic structures for sPPE have advanced, further supporting the continued relevance of the research topic. Recent applications have included auxetic helmet liners (D30, 2018; Foster et al., 2018; Bliven et al., 2019) and further development of footwear with auxetic soles (Hernandez, 2016; Kuerbis, 2016; Nickless, 2018) as well as research into sport safety applications generally (Duncan et al., 2016). Process developments of converting closed cell foam to exhibit negative Poisson's ratio (NPR) have been made (Fan et al., 2018) with potential for sPPE. However, conformability assessments and development of auxetic structures applied as body padding segmentation have remained novel to this research.

User perceptions of rugby body padding (Brisbine et al., 2020; Hughes et al., 2020) have received wider surveillance since this research began. However, investigating user perceptions at the start of this research, when it was not yet available, has been critical to progressing into commercial product assessments then leading to the development of auxetic alternatives. In addition, previous publications have focused on advancing knowledge of auxetic sPPE fabrication methods, rather than developing application methods and assessments. This research offers a unique perspective as it investigates and defines the problem with the existing product prior to the development and assessment of an auxetic alternative for an enhanced solution.

The findings of this PhD led to a recommended development strategy for sPPE with auxetic structures that provide enhanced conformability. It was adapted from design processes for other PPE types (Larson and Liverman, 2011; Watkins and Dunne, 2015) and begins with defining the problem via analysis of the user (Phase I) and the commercial standard (Phase II). Ideation and design of auxetic sPPE follow considering routes to enhanced conformability. The next stages (Phase III) were realised through development and tailoring of auxetic geometry for segmentation and analysis of the opening mechanisms under lateral expansion and synclastic curvature. The final product was compliant with the regulations for the World Rugby (2019b) Body Padding Specification, provided good pressure comfort and fit resulting in new knowledge of how auxetic structures can enhance the conformability of sPPE.

6.2 Fulfilment of the Research Objectives

Objective 1

The first objective of this research set out to evaluate current garment technology and wearer issues for sPPE and identify suitable auxetic structures and fabrication methods as an alternative. This objective was fulfilled through a comprehensive literature review (Chapter 2) of sPPE as well as auxetic structures and respective fabrication methods. The secondary research identified that sPPE can restrict mobility and lead to user discomfort often caused by pad bulkiness of materials including EVA which are joined to stretch sports tops. Segmentation has been used to improve pad bulkiness and conformability but the effects of different types of padding on user comfort were unknown. Pressure comfort assessments and fit assessments under active positions have been used to assess the effect of pad bulkiness on user comfort and fit, not yet investigated for rugby shoulder padding nor its different segmentation types. It has been found that user discomfort with other types of sPPE have contributed to poor product uptake and therefore user perceptions and product assessments of comfort were required to outline the standard of commercial padding.

In-plane auxetic structures were identified as a route to segmenting closed cell foams for sPPE. Auxetic structures benefit by exhibiting synclastic curvature and lateral expansion but further investigation was required to determine how these characteristics would affect sPPE product function. Research into NPR structures largely focuses on optimising fabrication methods and materials but sPPE applications have been limited to date. Therefore, integrating user-centred approaches including fit assessments involving pressure comfort assessments, body movement and curvatures into the research of auxetic sPPE were required. Fulfilling this gap was deemed necessary to determine recommendations for the use of sPPE with enhanced conformability.

Objective 2

The second objective required analysis of user perceptions of sPPE comfort as well as fit and pressure comfort recorded from commercial padding. A user perception survey established that a sample of rugby players perceived poor satisfaction with padding across the six realms of comfort and that user uptake was low. Fit and protection were identified as the most important realms of comfort to players when purchasing padding. However, fit and pressure comfort analysis of commercial padding reported poor pressure comfort and fit across all segmentation types but that specific fit issues were common to different segmentation types. Cut segmentation offered the best fit but poor pressure comfort, showing scope for improvement. Therefore, trade-offs between impact protection and conformability of sPPE do not meet user requirements requiring further development of padding with enhanced conformability.

Objective 3

The third objective applied knowledge of sPPE cut segmentation to a variety of auxetic structures. After development, the cut-segmented auxetic pads were inserted into the pocketed shoulder region of a rugby top and compared through assessments of tensile displacement, lateral expansion upon fitting to a mannequin, pressure comfort and impact over flat and curved anvils. With increased curvature and lateral expansion of the auxetic structures the segments were subject to opening out in different degrees of consistency throughout the pads. Pads that opened out least consistently were subject to higher peak forces in impact over curved anvils and were more likely to cause exposure to rugby injury. In addition, it was identified that the most desirable geometry for auxetic structures applied as sPPE cut-segmentation were shapes formed from singular cut lines as they led to the most consistent opening mechanism. The finding that opening mechanisms of different auxetic geometries had potential to provide less protective coverage and conformability depending on the consistency of the opening mechanism was novel to this research. Auxetic geometries in arrangements of singular cut lines maintained more consistent opening mechanism under tensile displacement.

Objective 4

The fourth objective developed the optimal shape from objective 3 through manipulation of its geometry. Manipulations of cut widths, rib lengths and anisotropy were applied resulting in new knowledge of how tailoring geometry of an auxetic structure affects its behaviour in relation to sPPE. Identical assessment methods from objective 3 were repeated and showed that anisotropy can be applied to control extension in specific directions with particular benefit for sPPE protecting joints without rotational movements, such as the knee cap. It was also discovered that increasing the difference between rib length and separation between ribs decreased the ability for the structure to open out. This could be applied at specific body regions where the skin is subject to greater expansion under movement such as at the top of the shoulder, to restrict opening out and prevent higher exposure to injury. In contrast, increased cut widths of the structure led to poorer conformability compared to the original structure. A recommended design strategy was produced for developing sPPE with auxetic structures for enhanced conformability.

6.3 Contribution to Knowledge

The outcomes of this PhD are of benefit to theoretical and practical knowledge practitioners of auxetic structures, sPPE and combined. The research findings have potential to guide pad designers, and influence sporting body regulations and future academic research. This section outlines the contribution to knowledge of the PhD and areas in which it has been restricted. The benefits of this research are owed to the novelty of its approach through use of interdisciplinary methods. The research has been examined through the lens of methods owed to mixed-fields including social and applied sciences as well as functional design.

Originality of the Research

In this research, investigations of NPR included physical testing of the pads embedded within a top fitted to a mannequin. Auxetic structures of different geometries were developed and assessed in respect to body curvature and movements including through pressure comfort assessments. This approach was undertaken due to the pragmatic perspective of the research which investigated ideas through corresponding practical effects and consequences (Goldkuhl, 2004). Previous publications have not yet explored physical testing of NPR in relation to body curvatures, lending originality to this research.

The PhD culminated in a recommended design process for sPPE with auxetic structures. Previous research of auxetic structures has advised sPPE applications but not derived or defined parameters for its effective use. This research is novel in that it not only outlines a strategy for designing sPPE with auxetic structures for enhanced conformability but defines parameters for its use. Parameters identified in this research relate to unit cell geometry and the resulting effect on its opening mechanism under lateral displacement.

Previous research into the effectiveness of rugby shoulder padding has focused on impact protection. Additionally, the World Rugby (2019b) Body Padding Specification provides impact test methods for assessing shoulder padding and recommends that products must not disrupt comfort or mobility but do not stipulate related performance assessments. In contrast this research is unique in that it investigated the fit and pressure comfort of commercial padding. The pads were assessed in respect to their segmentation types. No previous assessments of sPPE have been published in relation to the conformability of different segmentation types. Differences between segmentation types were found to affect both pressure comfort and conformability with cut-segmented pads proving to be the most effective. Pressure comfort measurements in combination with fit assessments under active body positions could be adopted by the World Rugby (2019b) Body Padding Specification for performance assessments of padding comfort.

Contribution to Theory

The outcomes of this PhD have attributed to the theoretical knowledge base of auxetic structures. Chapter 2 identified that published auxetic research had not yet determined whether exploiting auxetic structures for the novel ability to laterally expand under tensile displacement and over curved surfaces would affect the function of sPPE. Through conducting this study parameters for the effective use of auxetic structures for this purpose were formed. In particular, the research demonstrated how opening mechanisms of auxetic structures are affected by respective unit cell geometries and the space which divides them. This information will translate to other fields applying auxetic structures for the ability to laterally expand and in turn open out.

Contribution to Practice

The functional design aspect of this research led to the production of a design strategy. This acts to guide future research and development of auxetic sPPE, owed to the pragmatic research perspective. The design strategy enabled the fulfilment of the gap identified in the literature review for which research of the practical effects of auxetic structures for sport applications largely neglect the user. Physical assessments of developed auxetic materials for PPE applications will benefit from pressure comfort assessments and impact tests featuring anvils that model body curvatures. Through this it is possible to explore the practical effects and user experience of auxetic structures which have user-centred applications.

6.4 Limitations of the Research

The research conducted in this study was subject to limitations, which can be addressed in future research. The main output of the research was a recommended strategy for developing sPPE with auxetic elements influenced by user-centred design strategies for functional clothing (Watkins and Dunne, 2015) and healthcare PPE (Larson and Liverman, 2011). However, incorporating a user centred design strategy into the methods employed for Phases I – III could have benefited the research by seeking participant feedback to the developed auxetic sPPE. Feedback could have been sought through wearer trials as is strategized in the user centred design of functional clothing (Watkins and Dunne, 2015). Regardless, the mechanical and quantitative methods employed in this research were sufficient for identifying how auxetic structures can offer sPPE enhanced conformability.

Phase I

The user perception survey was conducted to determine rugby player satisfaction levels for shoulder padding across the six realms of comfort. The survey obtained quantitative data through questions comprised of Likert scales and rank order. However, through not utilising qualitative data collection, personal opinions of commercial products were neglected. Qualitative questions would have enabled the incorporation of functional clothing user-centred design approaches into Phase I of this research, through ascertaining personal feedback of commercial products (Watkins and Dunne, 2015). Regardless, in order to dispel and support current knowledge of padding, quantitative data collection was considered suitable for Phase I.

Phase II

Commercial rugby shoulder padding was assessed in relation to the fit and pressure comfort provided during active positions. This study utilised 9 tops representative of the 3 main segmentation types used within these garments. Although representative of the segmentation types, segments and pads vary greater across scale, shape and geometrical orientation in the market. However, segmentation design for padding is not regulated as such and there is a lack of research into critical zones of coverage within the shoulder region meaning that the padding market varies largely. Additionally, the sample of pads analysed in this study were enough for drawing conclusions about fit and pressure comfort patterns relating to segmentation type, which has not investigated comprehensively before.

This research focused on obtaining quantitative data to assess the conformability of commercial rugby shoulder padding. By analysing the pressure comfort measurements taken during different arm positions the effect of movement on fit was determined, providing an insight into which pads conformed better to shoulder movements. In contrast, user-centred design strategies define the design problem by taking into account user needs through qualitative research methods. Embedding subjective fit analysis through wearer trials could have benefited the pragmatic approach of this research by determining perceived comfort during use. However, future pad designers incorporating the strategy stipulated in this research will be able to incorporate user feedback amongst other user-centred design principles into the development process.

Phase III

The final phase of this study developed and assessed the effect of auxetic unit cell geometry on padding function and conformability. There were limitations to the tensile tests utilised in the study, in particular tensile samples were not featured in the test which would have enabled accurate calculations of Poisson's ratio. However, Poisson's ratio has been calculated for the different auxetic shapes utilised in this study and in contrast to previous research this explored the effect of pad and segmentation geometry on lateral displacement under tensile displacement. The shapes utilised for this study were a small selection of a wide array of possible auxetic structures and geometries. As such, there are opportunities for investigation of other auxetic structures in future research.

Utilising a high-speed camera for impact tests would have provided a visual description of the difference in deformation of pads with time. However, peak force was sufficient for describing the change in peak forces with increased curvature of anvil for different segmentation patterns. Additionally, degradation of pads was observed between impact tests and future research should document padding appearance between tests. Auxetic structures comprised of ligaments due to an arrangement of intersecting cut lines were found to exhibit higher peak forces and analysing padding appearance could determine whether this is because ligaments were subject to greater degradation. Additionally, this research ascertained that opening mechanism consistency affected peak forces. However, it was unknown what the relative density of each pad was on flat, cylindrical or domed surfaces, as such future research should examine the relative density of different auxetic segmentation patterns and its effect on impact tests over flat, cylindrical and domed anvils.

6.5 Recommendations for Future Research

Conventional closed cell foams were segmented with auxetic structures in this study but auxetic through-the-thickness closed cell foams are under development. Future research should investigate whether auxetic closed cell foams improve the conformability of vacuum moulded padding. Vacuum moulded auxetic through-the-thickness padding could be of benefit compared to cut-segmented because the pads do not leave the body exposed through opening out. In addition, auxetic through-the-thickness closed cell foams have shown potential to reduce peak forces under impact tests. This research found that improving the protection provided by padding could encourage product use and therefore future research of rugby shoulder padding should focus on optimising these foams.

Sustainability was not a consideration for the materials and methods in this research. However, there is increased pressure for brands to reduce their environmental impacts and pad designers utilising these findings should look to implement eco-conscious materials and production methods. Non-biodegradable EVA foam was utilised for this research and was identified as the industry standard for rugby shoulder padding. However, low C02 emitting alternatives or those comprised of recycled materials should be considered in future for padding. Additionally, optimisation of auxetic open and closed cell foams should look to improve the sustainability of the heat-based production methods for future applications in sPPE.

Impact tests over curved anvils were found to increase peak forces for pads segmented with some auxetic structures more so than the non-auxetic honeycomb used for comparison. This showed the importance of assessing the impact protection of auxetic sPPE over curved anvils. Future developments of anvils with realistic body region curvatures and stiffness will enable pad developers to adopt more realistic impact tests. Additionally, previous research found that force reduction was limited within the padded region on the body and anvils mimicking body regions will enable further investigation of this before pads are worn by players. This research also found that pad designs generally do not utilise the maximise zone of coverage as a compromise with conformability, locating critical regions of the shoulder for protection would could help to inform the design of the most suitable pad size and position.

Pressure comfort analysis described the effect of padding fit in this study from a front and back location of the shoulder. This method is recommended for pad designers analysing the user experience of sPPE. Future assessments should measure more locations within the protective region to ensure that pressure comfort is consistent throughout the pad. In addition, an ideal pressure range for shoulder padding did not exist and had to be defined for this study. Future research could investigate and validate a smaller range to be used for assessing the effect of padding on player movement and comfort.

References

Abdelmalek, A. (2019) 'Stitchless dorsal padding for protective sports gloves and other protective gear.' US patent application: US10201744B2.

Abounaim, M. D., Hoffmann, G., Diestel, O. and Cherif, C. (2009) 'Thermoplastic composite from innovative flat knitted 3D multi-layer spacer fabric using hybrid yarn and the study of 2D mechanical properties.' *Composite Science and Technology*, 70(2), pp. 363-370.

Age, L. (2011) 'Grounded theory methodology: positivism, hermeneutics, and pragmatism.' *The Qualitiative Report*, 16(6), pp. 1599-1615.

Aguilar, M. (2014) *Under Armour's Clutchfit Shoes Conform to the Shape of Your Movement.* 1st April. Gizmodo UK. [Online] [Accessed on 23rd June 2017] http://www.gizmodo.co.uk/2014/04/under-armours-clutchfit-shoes-conform-to-the-shape-of-your-movement/

Akenhead, R. and Nassis, G. P. (2016) 'Training load and player monitoring in high-level football: current practice and perceptions.' *International Journal of Sports Physiology and Performance*, 11(5), pp. 587-593.

Alderson, A. and Alderson, K. L. (2007) 'Auxetic materials.' *Journal of Aerospace engineering*, 221(4), pp. 565-575.

Alderson, A., Alderson, K. L., Chirima, G., Ravirala, N. and Zied, K. M. (2010) 'The in-plane linear elastic constants and out-of-plane bending of 3-coordinating ligament and cylinder-ligament honeycombs.' *Composites Science and Technology*, 70(2010), pp. 1034-1041.

Alderson A., Alderson K. L., Davies P. J. and Smart G. M. (2005) ‘The effects of processing on the topology and mechanical properties of negative Poisson's ratio foams.’ *Proceedings of the ASME Aerospace Division*, 70(2005), pp. 503-510.

Alderson, A., Alderson, K. L., McDonald, S. A., Mottershead, B., Nazare, S., Withers, P. J. and Yao, Y. T. (2013) ‘Piezomorphic materials.’ *Macromolecular Materials and Engineering*, *298*(3), pp. 318-327.

Alderson, A. and Evans, K. E. (2001) ‘Rotation and dilation deformation mechanisms for auxetic behavior in the α-cristobalite tetrahedral framework structure.’ *Physics and Chemistry of Minerals*, 28(10), pp. 711-718.

Alderson, K. L, Alderson, A., Ravirala, N., Simkins, V. and Davies, P. (2012) ‘Manufacture and characterization of thin flat and curved auxetic foam sheets.’ *Phys. Status Solidi B*, 249(7), pp. 1315-1321.

Alderson, K. L., Pickles, A. P., Neale, P. J. and Evans, K. L. (1994) ‘Auxetic polyethylene: the effect of a negative Poisson’s ratio on hardness.’ *Acta Metall Mater*, 42(7), pp. 2261-2266.

Allen, T., Duncan, O., Foster, L., Senior, T., Zampieri, D., Edeh, V. and Alderson, A. (2015) ‘Auxetic foam for snow-sport safety devices’ *Snow Sports Trauma and Safety,* 21(2017), pp. 145-159.

Allen, T., Hewage, T., Newton-Mann, C., Wang, W., Duncan, O. and Alderson, A. (2017) ‘fabrication of auxetic foam sheets for sports applications.’ *Physica Status Solidi b*, 254(12).

Allen, T., Shepherd, J., Hewage, T. A. M., Senior, T., Foster, L. and Alderson, A. (2015) ‘Low-kinetic energy impact response of auxetic and conventional open-cell polyurethane foams.’ *Phys. Status Solidi Basic Res*, 9(2015), pp. 1631-1639.

Andrade, C. (2017) ‘Age as a variable: continuous or categorical?’ *Indian J Psychiatry*, 59(4), pp. 524-525.

Ankrah, S. and Mills, N. J. (2003) ‘Performance of football shin guards for direct stud impacts.’ *Sports Engineering*, 6(207).

Arensdorf, S. and Tobergte, E. (2005) ‘Athletic protective padding.’ US patent application: US20060179545A1.

Ashby, M. F., Gibson, L. J., Wegst, U. and Olive, R. (1995) ‘The mechanical properties of natural materials I: material property charts.’ *Proceedings of the Royal Society A,* 450(1995), pp. 123-140.

ASTM. (2004) *F1446-04: Standard test methods for equipment and procedures used in evaluating the performance characteristics of protective headgear.* West Conshohocken: ASTM International. [Online] [Accessed on 19th October 2018] https://www.astm.org/Standards/F1446.htm

ASTM. (2012) *F2792-12a: Standard terminology for additive manufacturing technologies.* West Conshohocken: ASTM International. [Online] [Accessed on 20th September 2018] https://www.astm.org/Standards/F2792.htm

ASTM. (2017) *D3574: Standard test methods for flexible cellular materials – slab, bonded, and molded urethane foams.* West Conshohocken: ASTM International. [Online] [Accessed on 10th January 2019] https://www.astm.org/Standards/D3574.htm

ASTM. (2018) *F1154-18: Standard practices for evaluating the comfort, fit, function, and durability of protective ensembles, ensemble elements, and other components*. West Conshohocken: ASTM International. [Online] [Accessed on 26th April 2019] https://www.astm.org/Standards/F1154.htm

ASTM. (2019) *D5035 – 11: Standard test method for breaking force and elongation of textile fabrics (strip method).* West Conshohocken: ASTM International. [Online] [Accessed on 16th June 2019] https://www.astm.org/Standards/D5035.htm

Austin, H. W., Miller, J. C., Snyder, R. B. and Neidhart, J. W. (1970) 'Foldable protective head enclosure.' US patent application: US3621841A.

Avelino, C. P. and Santos, A. F. (2012) 'Spherical and planar folding tessellations by kites and equilateral triangles.' *Australasian Journal of Combinatorics*, 53(2012), pp. 109-125.

Balamuth, C., Kuris, A. and Kleesattel, C. (1962) 'Ultrasonic welding.' US patent application: US3053124A.

Balslev, B. (2006) 'Tubular spacer fabric.' International patent number: WO2006015599A1.

Banerjee, A., Chitnis, U. B., Jadhav, S. L., Bhawalkar, J. S. and Chaudhury, S. (2009) 'Hypothesis testing, type I and II errors.' *Industrial Psychiatry Journal*, 18(2), pp. 127-131.

Barbour. (2014) *A barbour guide - Personal protective equipment.* Safety and Health Practitioner. [Online] [Accessed on 18th March 2019] https://www.shponline.co.uk/downloads/download-a-guide-to-ppe/

BBC Sport. (2019) *World Rugby launches campaign to increase participation in women's game*. 21st May. The BBC. [Online] [Accessed on 26th November 2019] https://www.bbc.co.uk/sport/rugby-union/48348245

Beaudette, E. and Park, H. (2016) 'Impact of seam types on thermal properties of athletic bodywear.' *Textile Research Journal*, 87(9), pp. 1052-1059.

Beer, J. and Bhatia, D. N. (2009) 'Shoulder injuries in rugby players.' *International* *journal of shoulder surgery,* 3(1), pp. 1-3.

Bell, E., McFarland, D., Williams, J. and Heiden, K. (2018) 'Analysis of apparel structural characteristics to determine effects on fit, performance, and cost of womens' athletic shirts.' *In* ANS Research Symposium. *ANS Research Symposium 9*. Louisiana Tech University, United States, 12th April.

Bekkum, J. E. Van., Williams, J. M. and Morris, P. G. (2011) 'Cycle commuting and perceptions of barriers: stages of change, gender and occupation.' *Health. Edu,* 111(6), pp. 476-497.

Bensaid, S., Osselin, J-F., Schacher, L. and Adolphe, D. (2010) 'The effect of pattern construction on the tactile feeling evaluated through sensory analysis.' *The Textile Institute*, 97(2), pp. 137-145.

Bentham, M., Alderson, A. and Alderson, K. L. (2008) 'Garments having auxetic foam layers.' US patent application: US7455567B2.

Berger, J, G., Horsrud, J., Tolfsen, U. and Kristiansen, R. (2005) 'Helmet, helmet liner and method for manufacturing the same.' US patent application: US7676854B2.

Bhattacharya, S., Zhang, G. H., Ghita, O. and Evans, K. E. (2014) 'The variation in Poisson's ratio caused by interactions between core and wrap in helical composite auxetic yarns.' *Composites Science and Technology*, 102(2014), pp. 87-93.

Bianchi, M., Scarpa, L. M. and Smith, W. C. (2008) 'Stiffness and energy dissipation in polyurethane auxetic foams.' *Journal of Materials Science*, 43(17), pp. 5851-5860.

Birrer, R. B. and Anderson, M. K. (2002) 'Protective and supportive equipment.' *In* Birrer, R.B., Griesemer, B.A. and Cataletto, M.B. (eds.) *Pedriatric sports medicine for primary care*. Philadelphia: Lippincott Williams and Wilkins, pp. 103-116.

Blacker, J. (2012) *Auxetic fabric technology development for military protective clothing.* Navy. [Online] [Accessed on 15th February] http://www.navysbir.com/12_A/29.htm

Bliven, E., Rouhier, A., Tsai, S., Willinger, R., Bourdet, N., Deck, C., Madey, S. M. and Bottland, M. (2019) 'Evaluation of a novel bicycle helmet concept in oblique impact testing.' *Accident Analysis and Prevention*, 124(2019), pp. 58-65.

Boria, F. (2016) 'Back protector.' US patent application: US20190191794A1.

Borreguero, A. M., Rodriguez, J. F., Valverde, J. L. Peijs, T. and Carmona, M. (2012) 'Characterization of rigid polyurethane foams containing microencapsulated phase change materials: microcapsules type effect.' *Journal of Applied Polymer Science*, 128(1).

Braganca, S., Arezes, P., Carvalho, M. and Ashdown, S. (2016) 'Effects of different body postures on anthropometric measures.' *In* Applied Human Factors and Ergonomics. *Proceedings of the AHFE 2017 International Conference on Ergonomics in Design.* Vol 588. The Westin Bonaventure Hotel, Los Angeles, California, USA , 17th-21st July 2017. Rebelo. F., and Soares, M. (eds.).

Braham, R. A., Finch, C. F., McIntosh, A. and McCrory, P. (2004) 'Community football players' attitudes towards protective equipment – a pre-season measure.' *British Journal of Sports Medicine*, 38(4), pp. 426-430.

Brandt, B. C. (2018) 'Modular impact protection system for athletic wear.' US patent application: US10021922B2.

Branley, D., Covey, J. and Hardey, M. (2014) *Online surveys: investigating social media use and online risk*. London: SAGE Research Methods Cases.

Bransen, J. (2001) 'Unity of science.' *In* Smelser, N. J. and Baltes, P. B. (eds.) *International Encyclopedia of the Social and Behavioural Sciences*. London: Elsevier, pp. 16165-16170.

Brennan-Craddock, J., Brackett, D., Wildman, R. and Hague, R. (2012) 'The design of impact absorbing structures for additive manufacture.' *Journal Physics Conference Series*, 382(1).

Brisbine, B. R., Steele, J. R., Phillips, E. J. and McGhee, D. E. (2019) 'The occurrence, causes and perceived performance effects of breast injuries in elite female athletes.' *J Sports Sci Med*, 18(3), pp. 569-576.

Brisbine, B. R., Steele, J. R., Phillips, E. J. and McGhee, D. E. (2020) 'Use and perception of breast protective equipment by female contact football players.' *Journal of Science and Medicine in Sport*, 23(9), pp. 820-825.

British Columbia Injury Research and Prevention Unit (BCIRU). (2013) *Sport and Recreation*. [Online] [Accessed on 20th December 2016] https://www.injuryresearch.bc.ca/quick-facts/sport-recreation/#QF

Brooks, J. H. M., Fuller, C. W., Kemp, S. P. T. and Reddin, D. B. (2005) 'Epidemiology of injuries in English professional rugby union: part 1 match injuries.' *British Journal of Sports Medicine*, 39(10), pp. 757-766.

Brooks, J. H. M. and Kemp, S. P. T (2011) 'Injury-prevention priorities according to playing position in professional rugby union players.' *British Journal of Sports Medicine*, 45(10), pp. 765-775.

Brubacher, K., Apeagyei, P., Venkatraman, P. and Tyler, D. (2017) 'Design of sports compression garments: exploring the relationship between pressure distribution and body dimensions.' *In* Asia-Pacific Congress on Sports Technology. *8th Asia-Pacific Congress on Sports Technology: The Impact of Technology on Sport*. Vol. 2. Hilton Hotel, Tel Aviv, Israel, 15th – 19th October 2017. Subic, A., Scheinowitz, M., and Fuss, F.K. (eds.).

Bruer, S. M., Powell, N. and Smith, G. (2005) 'Three-dimensionally knit spacer fabrics: a review of production techniques and applications.' *Journal of Textile and Apparel*, 4(4), pp. 1-31.

Bruwer, E. J., Moss, S. J. and Jacobs, S. (2017) 'Injury incidence and selected biomechanical, postural and anthropometric characteristics contributing to musculoskeletal injuries in rugby union players.' *African Journal for Physical Activity and Health Sciences*, 23(1.2), pp. 172-189.

Bubonia, J. E. (2014) *Apparel quality: a guide to evaluating sewn products*. New York: Fairchild.

Busetto, L., Wick, W. and Gumbinger, C. (2020) 'How to use and assess qualitative research methods.' *Neurological Research and Practice*, 2(14).

Caddock, B. D. and Evans, K. E. (1994) 'Negative Poisson ratios and strain-dependent mechanical properties in arterial prosthese.' *Biomaterials*, 16(14), pp. 1109-1115.

Cahill, N., Lamb, K., Worsfold, P., Headley, R. and Murray, S. (2012) 'The movement characteristics of English premiership rugby union players.' *Journal of Sports Sciences*, 31(3), pp. 229-237.

Capp, J. (2019) 'The pragmatic theory of truth.' *In* Zalta, N,E. (ed.) *The Stanford Encyclopedia of Philosophy* (Summer 2019 Edition).

Carneiro, V. H., Meireles, J. and Puga, H. (2013) 'Auxetic materials – a review.' *Materials Science-Poland*, 31(4), pp. 561-571.

Carter, M. (2015) 'The unknown risks of youth rugby.' *BMJ*, 350(7990).

Caserta, G. D., Iannucci, L. and Galvanetto, U. (2011) 'Shock absorption performance of a motorbike helmet with honeycomb reinforced liner.' *Composite Structures,* 93(11), pp. 2748-2759.

Cattermole, H. R., Hardy, J. R. W. and Gregg, P. J. (1996) 'The footballer's fracture.' *Br J Sports Med*, 30(1996), pp. 171-175.

Cazon-Martin, A., Iturrizaga-Campelo, M., Matey-Munoz, L., Rodriguez-Ferradas, M. I., Morer-Camo, P. and Ausejo-Munoz, S. (2018) 'Design and manufacturing of shin pads with multi-material additive manufactured features for football players: a comparison with commercial shin pads.' *Proceedings of the Institute of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 233(1), pp. 160-169.

Challoner, S. (2016) *Open cell foam*. 24th February. Intec Foams. [Online] [Accessed on 24th January 2017] http://www.intecfoams.co.uk/foams/open-cell-foam/

Chan, E. and Evans, K. E. (1997) 'Fabrication methods for auxetic foams.' *Journal of materials science*, 32(1997), pp. 5945-5953.

Chan, N. and Evans, K. E. (1998) 'Indentation resilience of conventional and auxetic foams.' *Journal of Cellular Plastics,* 34(1998), pp. 231-260.

Chassagne, F., Molimard, J., Convert, R., Giraux, P., and Badel, P. (2016) 'Numerical approach for the assessment of pressure generated by elastic compression bandage.' *Annals of Biomedical Engineering*, 44(10), pp. 3096-3108.

Chen, C. P. and Lakes, R. S. (1996) 'Micromechanical analysis of dynamic behavior of conventional and negative Poisson's ratio foams.' *Journal Engineering Materials and Technology,* 118(1996), pp. 285-288.

Chin, W. K. and Wetzel, E. D. (2008) 'Breathability characterization of ballistic fabrics, including shear thickening fluid-treated fabrics.' Army Research Laboratory: ARL-TR-4392.

Choi, J. B. and Lakes, R. S. (1992) 'Nonlinear properties of polymer cellular materials with a negative Poisson's ratio.' *Journal of Materials Science,* 27(1992), pp. 5375-4684.

Chomiak, J., Junge, A. and Peterson, L. (2000) 'Severe injuries in football players. Influencing factors.' *Am J Sports Med*, 28(2000), pp. 58-68.

Chung, D. (2001) 'Review: materials for vibration damping.' *Journal of Material Science*, 36(24).

Ciullo, J. V. (1996) *Shoulder injuries in sport.* Leeds: Human Kinetics.

Classen, E. (2018) 'Comfort testing of textiles.' *In* Dolez, P., Vermeersch, O., and Izquierdo. (eds.) *Advanced characterization and testing of textiles*. Manchester: The Textile Institute Book Series, pp. 59-69.

Cobb, D. (2016) *A new kind of protective textile*. 8th July. Advanced Textiles Source. [Online] [Accessed on 15th January 2017] http://advancedtextilessource.com.previewdns.com /2016/07/a-new-kind-of-protective-textile/

Cooper, S. (2005) 'Protective fabric and apparel systems.' US patent application US4280342A.

Cooper, T., Oxborrow, L., Claxton, S., Goworek, H., Hill, H., Mclaren, A. (2017) 'New product developing and testing strategies for clothing longevity.' *In* PLATE: Product lifetimes and the environment*. Research in Design 2017 – Conference proceedings.* Vol 9. Delft University of Technology, Delft, the Netherlands, 8-10th November 2017. Bakker, C. A., and Mugge, R. (eds.).

Crawford, S. D., Couper, M. P. and Lamias, M. J. (2001) 'Web surveys: perceptions of burden.' *Social Science Computer Review*, 19(2), pp. 146-162.

Critchley, R., Corni, I., Wharton, J. A., Walsh, F. C., Wood, R. J. K. and Stokes, K. R. (2013) 'A review of the manufacture, mechanical properties and potential applications of auxetic foams.' *Physica status solidi (b)*, 250(10), pp. 1963-1982.

Cross, T. M., Hoffer, K. W. and Jones, D. P. (2015) 'Auxetic structures and footwear with soles having auxetic structures.' US patent application: 20150245685.

Crotty, M. (1998) *The foundations of social research: meaning and perspective in the research process*. London: Sage Publications.

Cubeddu, J. C. (2016) 'Lower leg sleeve.' US patent application: US20160374412A1.

D30. (2016) *Under Armour launches Gameday Armour Max Protection System*. [Online] [Accessed on 8th September 2018] https://www.d3o.com/under-armour-launches-gameday-armour-max-protection-system-featuring-d3o/

D30. (2017) *What is D30*. [Online] [Accessed on 6th December 2016] https://www.d3o.com/what-is-d3o/

D30. (2018) *Trust helmet pad system*. [Online] [Accessed on 12th September 2018] https://www.d3o.com/products/trust-helmet-pad-system/

D30. (2020a) *Sports protection*. [Online] [Accessed on 30th April 2020] https://www.d3o.com/our-products/sports-protection/

D30. (2020b) *How it works*. [Online] [Accessed on 19th January 2020] https://www.d3o.com/media/1209/d3o-how-it-works.ai

Dabolina, I. and Lapkovska, E. (2020) 'Sizing and fit for protective clothing.' *In* Zakaria, N., and Gupta, D. (eds.) *Anthropometry, Apparel Sizing and Design*. 2nd ed., London: Woodhouse Publishing.

Dabolina, I., Lapkovska, E. and Vilumsone, A. (2019) 'Dynamic anthropometry for investigation of body movement comfort in protective jacket.' *In* Majumdar A., Gupta, D., and Gupta, S. (eds.) *Functional Textiles and Clothing*. Singapore: Springer, pp. 241-259.

Das, A. and Alagirusamy, R. (2010) 'Introduction.' *In* Das, A., and Alagirusamy, R. (eds.) *Science in Clothing Comfort*. New York: WPI Publishing, pp. 159-201.

Das, A. and Ishtiaque, S. M. (2004) 'Comfort characteristics of fabrics containing twist-less and hollow fibrous assemblies in weft.' *Journal of Textile and Apparel, Technology and Management*, 3(4).

Decathlon UK. (2013) *How to Choose: Rugby Shoulder Pads*. 18th December. Decathlon UK. [Online]. [Accessed on 13th June 2017] http://blog.decathlon.co.uk/rugby/how-to-choose-rugby-shoulder-pads/

Diamond, R. (2012) 'Protective athletic garment.' US patent application: US20120240317A1.

Diamond, R. (2013) 'Protective athletic garment and method.' US patent application: US9067122B2.

Dillman, D. A. (2009) 'Methodology of longitudinal surveys.' UK: John Wiley and Sons.

Dolnicar, S., Grun, B. and Leisch, F. (2011) 'Quick, simple and reliable: forced binary survey questions.' *International Journal of Market research*, 53(2), pp. 231-252.

Domaschke, S., Morel, A., Fortunato, G. and Ehret, A. E. (2019) 'Random auxetics from buckling fibre networks.' *Nature Communications*, 10(2019), 4863.

Donoghue, J. P., Alderson, K. L. and Evans, K. E. (2009) 'The fracture toughness of composite laminates with a negative Poisson's ratio.' *Physcia Status Solidi (b)*, 246(9), pp. 2011-2017.

Duncan, O., Foster, L., Senior, T., Allen, T. and Alderon, A. (2016) 'A comparison of novel and conventional fabrication methods for auxetic foams for sports safety applications.' *Procedia Engineering,* 147(2016), pp. 384-389.

Duncan, O., Allen, T., Foster, L., Senior, T. and Alderson, A. (2017) 'Fabrication, characterisation and modelling of uniform and gradient auxetic foam sheets.' *Acta Materialia*.

Duncan, O., Allen, T., Foster, L., Gatt, R., Grima, J. and Alderson, A. (2018b) ‘Controlling density and modulus in auxetic foam fabrications for impact and indentation testing.’ *Proceedings,* 2(6).

Duncan, O., Shepherd, T., Moroney, C., Foster, L., Venkatraman, P. D., Winwood, K., Allen, T. and Alderson, A. (2018a) ‘Review of auxetic materials for sports applications: expanding options in comfort and protection.’ *Applied Sciences*, 8(941), pp. 1-33.

Dura, J. V., Garcia, A. C. and Solaz, J. (2002) ‘Testing shock absorbing materials: the application of viscoelastic linear model.’ *Sports Engineering*, 5(1), pp. 9-14.

Ekstrand, J., Healy, J. C., Walden, M., Lee, J. C., English, B. and Hagglund, M. (2012) ‘Hamstring Muscle Injuries in Professional Football: the Correlation of MRI Findings with Return to Play.’ *British Journal of Sports Medicine*, 46(2012), pp. 112-117.

Elipe, J. C. A. and Lantada, A. D. (2012) ‘Comparative study of auxetic geometries by means of computer-aided design and engineering.’ *Smart Materials and Structures*, 21(10).

English Oxford Living Dictionary. *Foam*. [Online] [Accessed on 12th January 2017] https://en.oxforddictionaries.com/definition/foam

European Committee for Standardisation. (2003a) EN14120. European Committee Standardization for protective clothing – wrist, palm, knee and elbow protectors for users of roller sports equipment – requirements and test methods.

European Committee for Standardisation. (2003b) EN1621. European Committee Standardization for Motorradfahrer Schutzkleidung Teil 2 Ruckenprotektroren.

Evans, K. E. (1991a) ‘Auxetic polymers: a new range of materials.’ *Endeavour*, 15(4), pp. 170-174.

Evans, K. E. (1991b) 'The design of doubly curved sandwich honeycomb cores.' *Composite structures,* 17(1991), pp. 95-111.

Evans, K. E. and Alderson, A. (2000) 'Auxetic materials: functional materials and structures from lateral thinking!' *Advanced Materials*, 12(9), pp. 617-628.

Evans, K. E., Nkansah, M. A. and Hutchinson, I. J. (1994) 'Auxetic foams: modelling negative poisson's ratio.' *Acta Metallurgica et Materiala*, 42(4), pp. 1289-1294.

Evans, K. E., Nkansah, M. A., Hutchinson, I. J. and Rogers, S. C. (1991) 'Molecular network design'. *Nature*, 353(6340), pp. 124-124.

Fan, D., Li, M., Qiu, J., Xing, H., Jiang, Z. and Tang, T. (2018) 'A novel method for preparing auxetic foam from closed-cell polymer foam based on steam penetration and condensation (SPC) process.' *Applied Materials & Interfaces*.

Farrell, D. T., McGinn, C. and Bennett, G. J. (2020) 'Extension twist deformation response of an auxetic cylindrical structure inspired by deformed cell ligaments.' *Composite Structures*, 238(2020).

Fédération Internationale de Football Association (FIFA). (2013) *Laws of the game*. 2013/14 ed. Zurich. [Online] [Accessed on 28th September 2019].

Ferguson, J. R. (2007) 'Impact shock absorbing material.' US patent application: US8087101B2.

Fie, S. M., Abrahams, S., Patricios, J., Suter, J., Posthumus, M. and September, A. V. (2018) 'The association between harm avoidance personality traits and self-reported concussion history in South African rugby union players.' *Journal of Science and Medicine in Sport*, 21(1), pp. 16-21.

Field, A. (2013) *Discovering Statistics Using IBM SPSS Statistics*. London: Sage Publications Ltd.

Fielding, N. G. (2012) 'Triangulation and mixed methods design: data integration with new research technologies.' *Journal of Mixed Methods Research*, 6(2), pp. 124-136.

Fila, T., Zlamal, P., Falta, J., Doktor, T., Koudelka, P., Kytyr, D., Adorna, M., Luksch, J., NeuhauserovToma, M., Valach, J. and Jirousek, O. (2018) 'Testing of auxetic materials using Hopkinson bar and digital image correlation.' *In* Conference on the mechanical and physical behaviour of materials under dynamic loading. *Proceedings of the 12th International Conference on the mechanical and physical behaviour of materials under dynamic loading.* University of Bordeaux, France. 9th – 14th September 2018. [Online] [Accessed on 10th March 2019] https://www.epjconferences.org/articles/epjconf/abs/2018/18/epjconf_dymat2018_02045/epjconf_dymat2018_02045.html

Finch, C. (2006) 'A new framework for research leading to sports injury prevention.' *Journal of Science and Medicine in Sport*, 9(2006), pp. 3-9.

Finch, C., McIntosh, A. S. and McCrory, P. (2001) 'What do under 15 year old schoolboy rugby union players think about protective headgear.' *British Journal of Sports Medicine*, 35(2).

Fink, A. (2015) *How to conduct surveys: a step-by-step guide.* London: SAGE Publications.

Fletcher, K. and Grose, L. (2012) 'Materials.' *In* Fletcher, K., and Grose, L. (eds.) *Fashion and sustainability: design for change*. London: Laurence King Publishing, pp. 12-32.

Flynn, J. Z. and Foster, I. M. (2009) *Research methods for the fashion industry*. New York: Fairchild Books.

Foster, L., Peketi, P., Allen, T., Senior, T., Duncan, O. and Alderson, A. (2018) ‘Application of auxetic foam in sports helmets.’ *Appli. Sci*, 8(3), pp. 354.

Frolich, L. M., Labarbera, W. P. and Stevens, W. P. (2009) ‘Poisson’s ratio of a crossed fibre sheath: The skin of aquatic salamanders.’ *Journal of Zoology*, 232(2), pp. 231-252.

Fuller, C. W., Clarke, L. and Molloy, M. G. (2010) ‘Risk of injury associated with rugby union played on artificial turf.’ *Journal of Sports Sciences,* 28(5), pp. 563-570.

Funk, L. (2012) The Rugby Shoulder. [Online] [Accessed on 14th April 2017] https://www.shoulderdoc.co.uk/article/755

Gatt, R., Mizzi, L., Azzopardi, J. I., Azzopardi, K. M., Attard, D., Casha, A., Briffa, J. and Grima, J. N. (2015) ‘Hierarchical auxetic mechanical metamaterials.’ *Scientific reports*, 5(8395).

Goldkuhl, G. (2004) ‘Meanings of pragmatism: ways to conduct information systems research.’ *In* Action in Language, Organisations and Information. *Proceedings of the 2nd International Conference on Action in Language, Organisations and Information.* Likoping, Sweden, 17th – 18th March, pp. 13-26. [Online] [Accessed on 3rd June 2017] http://www.vits.org/Konferenser/alois2004/html/6901.pdf

Goncalves, C. C. P., Magalhaes, R. M. P., Rana, S., Fangueiro, R., Nunes, J.P. and Dias, G.R. (2018) ‘Characterisation of auxetic and mechanical behaviours of auxetic composites developed using star knitted structures.’ *In* AuxDefense. *1st World Conference on Advanced Materials for Defense*. University of Minho, Portugal, 3rd – 4th September 2018. [Online] [Accessed on 1st February 2019] https://repositorium.sdum.uminho.pt/handle/1822/58442

Gooding, E. R. (1981) ‘Protective liner for outdoor headgear.’ US patent application: US4354284A.

Gordon, J. R., Ludwig, N. M., Monahan, B. J. and Anderson, B. C. (2015) 'Pad for a garment, padded garment and method of manufacturing same.' US patent application: US8931119B2.

Goud, V. S. (2010) 'Auxetic textiles.' *Colourage*, 57(6), pp. 45-48.

Gould, T. E., Jesunathadas, M., Nazarenko, S. and Piland, S. G. (2019) 'Mouth protection in sports.' *In* Subic, A. (ed.) *Materials in Sports Equipment*. London: Woodhouse Publishing.

Govindaraj, P. and Sudhakar, M. S. (2018) 'Hexagonal grid based triangulated feature descriptor for shape retrieval.' *Pattern Recognition Letters*, 116(2018), pp. 157-163.

Gratton, C. and Jones, I. (2010) *Research methods for sports*. London: Routledge.

Greaves, G. N., Greer, A., Lakes, R. S. and Rouxel, T. (2011) 'Poisson's ratio and modern materials.' *Nature Mater*, 10(11), pp. 823-837.

Griffiths, P. M. (2009) 'Animal shoe.' US patent application: US20110209883A1.

Grima, J. N., Chetcuti, E., Manicaro, E., Attard, D., Camilleri, M., Gatt, R. and Evans, K. E. (2012) 'On the auxetic properties of generic rotating rigid triangles.' *Proceedings of the Royal Society A,* 468(2139), pp. 810–830.

Grima, J, N. and Evans, K. E. (2000) 'Auxetic behaviour from rotating squares.' *Journal of Material Science*, 19(17), pp. 1563–1565.

Grima, J. N. and Evans, K. E. (2006) 'Auxetic behaviour from rotating triangles.' *Journal of Material Science*, 41(10), pp. 3193-3196.

Grima, J. N., Manicaro, E. and Attard, D. (2011) 'Auxetic behaviour from connected different-sized squares and rectangles.' *Proceedings: Mathematical, Physical and Engineering Sciences*, 467(2126), pp. 439-458.

Grimmelsmann, N., Meissner, H. and Ehrmann, A. (2016) '3D printed auxetic forms on knitted fabrics for adjustable permeability and mechanical properties.' *IOP Conference Series: Materials Science and Engineering*, 137(2016).

Guo, Y. B., Gao, G. F., Jing, L. and Shim, V. P. W. (2017) 'Response of high-strength concrete to dynamic compressive loading.' *International Journal of Impact Engineering*, 108(2017), pp. 114-135.

Harris, D. and Spears, I. R. (2010). 'The effect of rugby shoulder padding on impact force attenuation.' *British Journal of Sports Medicine,* 44(3), pp. 200-203.

Harrison, A. J., McErlain-Naylor, S. A., Bradshaw, E. J., Dai, B., Nunome, H., Hughes, G. T. G., Kong, P. W., Vanwanseele, B., Vilas-Boas, J. P., Fong, D. T. P. (2020) 'Recommendations for statistical analysis involving null hypothesis significance.' *Sports Biomechanics*, 19(5), pp. 561-568.

Hayes, S. G. (2018) 'Joining techniques for high-performance apparel.' *In* Mcloughlin, J., and Sabir, T. (eds.) *High-performance apparel.* London: Woodhouse Publishing, pp. 157-171.

Helgeson, K. and Stoneman, P. (2014) 'Shoulder injuries in rugby players: mechanisms, examination and rehabilitation.' *Physical Therapy in Sport*, 15(4), pp. 218-227.

Hendricks, S. and Lambert, M. (2010) 'Tackling in rugby: coaching strategies for effective technique and injury prevention.' *International Journal of Sports Science and Coaching*, 5(1), pp. 117-135.

Hernandez, R. (2016) 'Shoe outsole.' US patent application: USD812356S1.

Higg Material Sustainability Index. (2018) *Ethylene-vinyl Acetate (EVA), fossil fuel based*, [Online] [Accessed on 1st October 2018] https://msi.higg.org/process/60/ethylene-vinyl-acetate-eva-fossil-fuel-based?return=%2Fsac materials%2Fdetail%2F141%2Fethylene-vinyl-acetate-eva-foam

Horevoorts, N. J. E., Vissers, P. A. J., Mols, F., Thong, M. S. Y. T. and van de Poll-Franse, L. V. (2015) ‘Response rates for patient-reported outcomes using web-based versus paper questionaires: comparison of two invitational methods in older colorectal cancer patients.’ *Journal of Medical Internet Research*, 17(5).

Hou, Y., Neville, R., Scarpa, F., Remillat., Gu, B. and Ruzzene, M. (2014) ‘Graded conventional-auxetic kirigami sandwich structures: flatwise compression and edgewise loading.’ *Composites: Part B*, 59(2014), pp. 33-42.

Howell, B., Prendergast, P. and Hansen, L. (1991) ‘Acoustic Behaviour of Negative Poisson’s Ratio Materials DTRC-SME-91/01.’ *David Taylor Research Centre, Annapolis, MD.*

Huang, F., Yan, B. and Yang, D. (2002) ‘The effects of material constants on the micropolar elastic honeycomb structure with negative Poisson's ratio using the finite element method.’ *Engineering Computations*, 19(7), pp. 742-763.

Huang, H. H., Wong, B. L. and Chou, Y. C. (2016) ‘Design and properties of 3D-printed chiral auxetic metamaterials by reconfigurable connections.’ *Phys. Status Solidi Basic Res,* 253(2016), pp. 1557-1564.

Hughes, A., Carre, M. and Driscoll, H. (2020) ‘Perceptions and attitudes towards shoulder padding and shoulder injury in rugby union.’ MedRxiv.

Hu, H., Wang, Z. and Liu, S. (2011) ‘Development of auxetic fabrics using flat knitting technology.’ *Textile Research Journal*, 81(14), pp. 1493-1502.

Hui, H. D. G. (2014) ‘Method for preparing sportswear protection pad, and protection pad obtained by using method.’ US patent application: US20170295863A1.

Hunter, M. (2016) 'What is design and why it matters.' [Online] [Accessed November 15th 2020] http://www.thecreativeindustries.co.uk/uk-creative-overview/news-and-views-view-w

Hur, P., Rosengren, K. S., Horn, G. P., Smith, D. L. and Hsiao-Weckster, E. T. (2013) 'Effect of protective clothing and fatigue on functional balance of firefighters.' *J Ergonomics S2.*

Ilieva, J., Baron, S. and Healey, N. M. (2002) 'Online surveys in marketing research: pros and cons.' *International Journal of Market Research*, 44(3), pp. 361-382.

Jacobs, B. and Sellars, N. (2019) 'The evolution of women's rugby.' *In* Lough, N. and Geurin, A. N. (eds.) *Routledge Handbook of the Business of Women's Sport*. New York: Routledge.

Jewell, G. L. D., Kitteringham, R. G., Dickie, R. G. and Copeland, S. (2006) 'Athletic pants with integral knee support.' US patent application: US7496973B2.

Jiang, Y. and Li, Y. (2016). '3D printed chiral cellular solids with amplified auxetic effects due to elevated internal rotation.' *Advanced Engineering Materials*, 10(1002).

Jin, Z., Yan, Y., Luo, X. and Tao, J. (2008) 'A study on the dynamic pressure comfort of tight seamless sportswear.' *Journal of Fiber Bioengineering and Informatics, 1(3).*

Jirousek, O., Koudelka, P. and Fila, T. (2015) 'Mechanical properties of auxetic structures produced by additive manufacturing.' *International Conference Engineering Mechanics*, 231(2015), pp. 124-125.

Jones, S. R., Carley, S., and Harrison, M. (2004) ' An introduction to power and sample size estimation.' *Emergency Medical Journal*, 20(5), pp. 453-458.

Joun, M., Choi, I., Eom, J. and Lee, M. (2007) 'Finite element analysis of tensile testing with emphasis on necking.' *Computational Materials Science,* 41(1), pp. 63-69.

Jupp, V. (2006) *The Sage Dictionary of Social Research Methods*. London: Sage Publications.

Kabir, Md. E., Saha, M. and Jeelani, S. (2006) 'Tensile and fracture behaviour of polymer foams.' *Materials Science and Engineering*, 429(1-2), pp. 225-235.

Kajtaz, M., Subic, A., Brandt, M. and Leary, M. (2019) 'Chapter 5 – three-dimensional printing of sports equipment.' *In* Subic, A. (ed*.) Materials in sports equipment*. 3rd ed., London: Woodhouse Publishing, pp. 161-198.

Kalveram, S. (2016) *3D printed chiral cellular solids with amplified auxetic effects*. Advanced Science News. [Online] [Accessed on 10th February 2017] http://www.advancedsciencenews.com/3d-printed-chiral-cellular-solids-amplified-auxetic-effects/

Kamrava, S., Mousanezhad, D., Ebrahmi, H., Ghosh, R. and Vaziri, A. (2017) 'Origami-based cellular metamaterial with auxetic, bistable and self-locking properties.' *Science*, 7(46046), pp. 1-9.

Kar, J., Fan, J. and Yu, W. (2006) 'Performance evaluation of knitted underwear.' *In* Yu, W., Fan, J., Harlock, S. C. and Ng, S. P. (eds.) *Innovation and Technology of Women's Intimate Apparel*. London: Woodhead Publishing Series in Textiles, pp. 196-222.

Kayseri, G. O., Ozdil, N. and Menguc, G. S. (2012) 'Sensorial comfort of textile materials.' *In* Jeon, H. (ed.) *Woven Fabrics*. London: Technology and Engineering, pp. 235-266.

Kazemi, M., Shearer, H. and Choung, Y. S. (2005) 'Pre-competition habits and injuries in Taekwondo athletes.' *BMC Musculoskeletal Disorders*, 6(26).

Kerr, J. H. (2018) 'The enjoyment of sanctioned aggression in rugby: the experience of a pioneering female canadian team captain.' *International Journal of Sport and Exercise Psychology*, 17(6), pp. 578-590.

Khaburi, J. A., Denhghani-Sanij, A. A., Nelson, A. and Hutchinson, J. (2011) 'Measurement of interface pressure applied by medical compression bandages.' *In* Insititute of Electrical and Electronics Engineers. *Proceedings of 2011 Institute of Electrical and Electronics Engineers International Conference on Mechatronics and Automation*. Beijing, China, 7th – 10th August 2011, pp. 289-294. [Online] [Accessed on 11th July 2017] https://ieeexplore.ieee.org/abstract/document/5985672

Kirk, Jr. W. and Ibrahim, S. M. (1966) 'Fundamental relationship of fabric extensibility to anthropometric requirements and garment performance.' *Textile Research Journal,* 36(1), pp. 37-47.

Kishner, S. (2015) *Shoulder Joint Anatomy*. 12th August. Medscape. [Online] [Accessed on 10th January 2017] http://emedicine.medscape.com/article/1899211-overview

Klossner, D. (2013) *Sports Medicine Handbook*. The National Collegiate Athletic Association. [Online] [Accessed: 29th November 2016] https://www.ncaa.org/sites/default/files/SMHB%20Mental%20Health%20INterventions.pdf

Kolken, H. M. A. and Zadpoor, A. A. (2017) 'Auxetic mechanical metamaterials.' *RSC Advances,* 7(2017), pp. 5111-5129.

Kroncke, E. L., Niedfeldt, M. W. and Young, C. (2008) 'Use of protective equipment by adolescents in inline skating, skateboarding, and snowboarding.' *Clinical Journal of Sport Medicine*, 18(1), pp. 38-43.

Kuerbis, T. E. (2015) 'Shoe midsole.' US patent application: USD765362S1.

Laing, R. M. and Carr, D. J. (2015) 'Protection.' *In* Shishoo, R. (eds.) *Textiles in Sport.* Abingdon: Taylor and Francis Inc*,* pp. 233-261.

Lakes, R. S. (1987) 'Foam structures with a negative Poisson's ratio.' *Science*, 235(1987), pp. 1038-1040.

Lakes, R. S. and Elms, K. (1993) 'Indentability of conventional and negative Poisson's ratio foams.' *Journal of Composite Materials,* 27(1993), pp. 1193-1202.

Landauer, A. K., Li, X., Franck, C. and Hennan, D. L. (2019) 'Experimental characterization and hyperelastic Constitutive Modeling of Open-cell Elastomeric Foams.' *Journal of the Mechanics and Physics of Solids*, 133(2019).

Lao, S., Edher, H., Saini, U., Sixt, J. and Salehian, A. (2019) 'A novel capacitance-based in-situ pressure sensor for wearable compression garments.' *Micromachines*, 10(11), pp. 743.

Larson, E. L. and Liverman, C. T. (2011) 'Designing and engineering effective PPE.' *In* Preventing transmission of pandemic influenza and other viral respiratory diseases: personal protective equipment for healthcare personnel. Washington: National Academis Press.

Lee, J., Choi, J. B. and Choi, K. (1996) 'Application of homogenization FEM analysis to regular and reentrant honeycomb structures.' *J Mater Sci*, 31(15), pp. 4105–10.

Lees, C., Vincent, J. F. and Hillerton, J. E. (1991) 'Poisson's ratio in skin.' *Journal of Biomedical Material and Engineering,* 1(1), pp. 19-23.

Lee, S. K. and Kim, S. (2011) 'Snowboard wrist guards–use, efficacy, and design.' *Bulletin of the NYU Hospital for Joint Diseases*, 69(2), pp. 149-57.

Ledbury, J. (2018) 'Design and product development ' *In* High-performance apparel. London: Woodhouse Publishing Series in Textiles, pp. 175-189.

Lewis, W. J. (2003) ‘Introduction’ In *Tension structures: Form and behaviour* London: Thomas and Telford. pp. 1-19.

Liaqat, M., Samad, H. A., Hamdani, S. T. A. and Nawab, Y. (2017) ‘The development of novel auxetic structure for impact applications.’ *The Journal of The Textile Institute*, 108(7), pp. 1264 – 1270.

Lim, N., Yu, W. and Yip, J. (2006) ‘Innovation of girdles.’ *In* Yu, W., Fan, J., Harlock, S.C., and Ng, S.P. (eds.) *Innovation and Technology of Women’s Intimate Apparel*. London: Woodhouse Publishing, pp. 114-131.

Lim, T. (2014) ‘Introduction’ In *Auxetic Materials and Structures*. Singapore: Springer, pp. 1-38.

Lim, T. (2015) ‘Bending stresses in triangular auxetic plates.’ *J. Eng. Mater. Technol,* 138(1).

Lipton, J. I., MacCurdy, R., Manchester, Z., Chin, L., Cellucci, D. and Rus, D. (2018) ‘Handedness in shearing auxetics creates rigid and compliant structures.’ *Science*, 360(6389), pp. 632-635.

Lipton, J. I., MacCurdy, R., Chin, L. and Rus, D. (2018) ‘Non-planar shearing auxetic structures, devices, and methods.’ US patent application: US20180311833A1.

Li, S., Al-Badani, K., Gu, Y., Lake, M. J., Li, L., Rothwell, G. and Ren, J. (2017) ‘The effects of Poisson’s ratio on the indentation behaviour of materials with embossed system in an elastic matrix.’ *Physica Status Solidi (b)*, 254(12).

Li, T., Liu, F. and Wang, L. (2020) ‘ Enhancing indentation and impact resistance in auxetic composite materials.’ *Composites Part B: Engineering*, 198(2020), pp. 1 – 10.

Lisiecki, J., Błazejewicz, T., Kłysz, S., Gmurczyk, G., Reymer, P. and Mikułowski, G. (2013) 'Tests of polyurethane foams with negative Poisson's ratio.' *Phys. Status Solidi Basic Res*, 250(2013), pp. 1988–1995.

Liu, Q. (2006) 'Literature Review: Materials with Negative Poisson's Ratios and Potential Applications to Aerospace and Defence.' Defence Science and Technology Organisation.

Liu, Y., Au, W. M. and Hu, H. (2013) 'Protective properties of warp-knitted spacer fabrics under impact in hemispherical form. Part I: Impact behaviour analysis of a typical spacer fabric.' *Textile Research Journal*, 84(4), pp. 422-434.

Liu, Y. and Hu, H. (2010) 'A review on auxetic structures and polymeric materials.' *Scientific Research and Essays*, 5(10), pp. 1052-1063.

Liu, Y., Hu, H., Lam, J. and Liu, S. (2009) 'Negative Poisson's ratio weft-knitted fabrics.' *Textile Research Journal*, 80(9), pp. 856-863.

Liu, Y., Hu, H., Zhao, L. and Long, H. (2011) 'Compression behaviour of warp-knitted spacer fabrics for cushioning applications.' *Textile Research Journal,* 82(1), pp. 11-20.

Li, Y. and Wong, A. S. W. (2006) 'Dimensions of sensory clothing perceptions.' *In* Li, Y., and Wong, A. S. W. (eds.) *Clothing Biosensory Engineering*. London: Woodhead Publishing Series in Textiles, pp. 151-166.

Li, Y. and Zeng, C. (2016) 'On the successful fabrication of auxetic polyurethane foams: key insights from materials science and polymer processing perspectives.' *In* Florida State University. *Antec*. Indianapolis, May 23-25.

Low, V. (2015) *Don't protect kids for rugby, says Tindall.* 24th February. *The Times*. [Online] [Accessed on 25th November 2019] https://www.thetimes.co.uk/article/dont-protect-kids-for-rugby-says-tindall-n7vx2zpt63s#

Lymed. (2020) *A comparison of compression standards*. [Online] [Accessed on 19th January 2020] http://lymed.fi/en/treatment/a-comparison-of-compression-standards/

Malcolm, D., Sheard, K. and Smith, S. (2005) 'Protective equipment and the injury crisis in English Rugby Union.' *Football Studies,* 8(1), pp. 58-66.

Mander, W. J. (2008) 'Bradley's Logic.' *In* Gabbay, D. M., Woods, J. (eds.) *Handbook of the History of Logic*. Vol. 4., London: Elsevier, pp. 663-717.

Martin, P. G. (2011) 'Molded auxetic mesh.' US patent application: US20110159758A1.

Martz, E. O., Lee, T., Lakes, R. S., Goel, V. K. and Park, J. B. (1996) 'Re-entrant transformation methods in closed cell foams.' *Cellular Polymers*, 15(4), pp. 229-249.

Material District. (2015) *Orimetric*. [Online] [Accessed on 1st October 2018] https://materialdistrict.com/material/orimetric/#moved

Mattei, T. A., Bond, B. J., Goulart, C. R., Sloffer, C. A., Morris, M. J. and Lin, J. J. (2012) 'Performance analysis of the protective effects of bicycle helmets during impact and crush tests in pediatric skull models.' *Journal of Neurosurgery*, 10(6), pp. 490-497.

Mazzarolo, G. (2002) 'Motorcycling glove.' US patent application: US6715152B2.

McCann, J. and Bryson, D. (2014) *Textile-led design for the active ageing population*. London: Woodhouse Publishing Series in Textiles.

McCormack, T. M., Miller, R., Kesler, O. and Gibson. L. J. (2001) 'Failure of sandwich beams with metallic foam cores.' *International Journal of Solids and Structures*, 38(2001), pp. 4901-4920.

McIntosh, A. S. and McCrory, P. (2001) 'Effectiveness of headgear in a pilot study of under 15 rugby union football.' *British Journal of Sports Medicine*, 35(3).

McLoughlin, J. and Hayes, S. (2015), 'Joining techniques for sportswear.' *In* Shishoo, R. (ed.) *Textiles for Sportswear.* Victoria, Australia: Woodhouse Publishing, pp. 119-149.

McQuerry, M., Kwon, C. and Johnson, H. (2019) 'A critical review of female firefighter protective clothing and equipment workplace challenges.' *Research Journal of Textile and Apparel*, 23(2), pp. 94-110.

Miller, W., Hook, P. B., Smith, C. W., Wang, X. and Evans, K. E. (2009) 'The manufacture and characterization of a novel, low modulus, negative poisson's ratio composite.' *Composites Science and Technology*, 69(5), pp. 651-655.

Milosevic, P. and Bogovic, S. (2018) '3D technologies in individualized chest protector modelling.' *Textile and Leather Review*, 1(2), pp. 46-55

Mizzi, L., Salvati, E., Spaggiari, A., Tan, J. and Korsunsky, A. (2019) 'Highly stretchable two-dimensional auxetic metamaterial sheets fabricated via direct-laser cutting.' *International Journal of Mechanical Sciences,* 167(2020).

Montazer, M. A., Vyas, S. K. and Wentworth, R. N. (1987) 'A study of human performance in a sewing task.' *Proceedings of the Human Factors Society Annual Meeting,* 31(5), pp. 590-594.

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C. and Simms, C. (2018) 'Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases.' *Br J Sports Med*, 52(2018), pp. 994-1001.

Moore, I. S., Ranson, C. and Mathema, P. (2015) 'Injury risk in international rugby union: three-year injury surveillance of the Welsh national team.' *Orthopaedic Journal of Sports Medicine*, 3(7).

Morrell, R. (2017) 'Touch rugby, masculinity and progressive politics in Durban, south Africa, 1985-1990.' *The International Journal of the History of Sport*, 34(7-8).

Morrow, D. and Winningham, M. (2006) 'Protective glove having a padded palmless outer glove and form-fitting inner glove.' US patent application: US7530120B2.

Mott, P. H. and Roland, C. M. (2012) 'Limits to Poisson's ratio in isotropic materials – general result for arbitrary deformation.' *Physica Scripta*, 87(5), pp. 1-15.

Mountasir, A., Hoffmann, G. and Cherif, C. (2011) 'Development of weaving technology for manufacturing three-dimensional spacer fabrics with high-performance yarns for thermoplastic composite applications: an analysis of two-dimensional mechanical properties.' *Textile Research Journal*, 81(13), pp. 1354-1366.

Muslija, A. and Lantada, A. D. (2014) 'Deep reactive ion etching of auxetic structures: present capabilities and challenges.' *Smart Materials and Structures*, 23(8), pp. 1-7.

Myers-McDevitt, P. J. (2004) 'Complete guide to size specification and technical design.' New York: Fairchild.

Nayak, R., Kanesalingam, S., Vijayan, A., Wang, L., Padhye, R. and Arnold, L. (2017) 'Design of 3D knitted structures for impact absorption in sportswear.' *KnE Engineering*, 2(2), pp. 127-134.

Newman, D. (2003) 'A prospective study of injuries at first class counties in England and Wales 2001 and 2002 seasons' *In* Second World Congress of Science and Medicine in Cricket. Cape Town, South Africa. Stretch, R. A. (eds.).

Ng, W. S. and Hu, H. (2018) 'Woven fabrics made of auxetic plied yarns.' *Polymers*, 10(2), pp. 226.

NHS. (2015) *Sports injuries – examples*. 25th February. [Online] [Accessed on 7th January 2017]

Nickless, D. (2018) 'Shoe.' US patent application: USD872441S1.

Norris, C. M. (2005) Sports injuries : diagnosis and management. 3rd ed. ed., Edinburgh: Butterworth-Heinemann.

Onireti, O., Qadir, J., Imran, M. A. and Sathiaseelan, A. (2016) 'Will 5G see its blind side? Evolving 5G for universal internet access.' *In* GAIA. *Proceedings of the 2016 Workshop on Global Access to the Internet for All*. Florianopolis, Brazil, 22nd – 26th August 2016.

Orchard, J., Neman, D., Stretch, R., Frost, W., Mansingh, A. and Leipus, A. (2005) 'Methods for injury surveillance in international cricket.' *Journal of Sport and Medicine in Sport*, 8(1), pp. 1-14.

Oxford English Dictionary. (2018) *Foam*. [Online] [Accessed on 29th September 2018] https://en.oxforddictionaries.com/definition/foam

Paeglis, A, U. and Hinckley, P. D. (1987) 'Method for heat sealing thermoplastic membranes.' US patent application: US4737213A.

Pain, M. T. G., Tsui, F. and Cove, S. (2008) 'In vivo determination of the effect of shoulder pads on tackling forces in rugby.' *Journal of Sports Sciences*, 26(8), pp. 855-862.

Park, H., and Park, J., Lin, S-H. and Boorady, L, M. (2014) 'Assessment of firefighters' needs for personal protective equipment.' *Fashion and Textiles*, 1(8).

Park, J. H. and Lee, J. R. (2019) 'Developing fall-impact protection pad with 3D mesh curved surface structure using 3D printing technology.' *Polymers*, 11(11).

Partsch, H., Clark, M., Bassez, S., Bennigni, J, P., Becker, F, Blazek, V., Caprini, J., Cornu-Thenard, A., Hafner, J. and Flour, M. (2006) 'Measurement of lower leg compression in vivo: recommendations for the performance of measurements of interface pressure and stiffness.' *Dermatological Surgery*, 32(2006), pp. 224-233.

Payne, T., Mitchell, S., Halkon, B. and Bibb, R. (2016) 'A systematic approach to the characterisation of human impact injury scenarios in sport.' *BMJ Open Sport & Exercise Medicine*, 2(1).

Petchenik, J. and Watermolen, D. J. (2011) 'A cautionary note on using the internet to survey recent hunt education graduates.' *Human Dimensions of Wildlife*, 16(3), pp. 216-218.

Pienaar, E. F., Lew, D. K. and Wallmo, K. (2013) 'Are environmental attitudes influenced by survey context? An investigation of the context dependency of the new ecological paradigm (NEP) scale.' *Social Science Research*, 42(6), pp. 1542-1554.

Prawoto, Y. (2012) 'How to compute plastic zones of heterogeneous materials: a simple approach using classical continuum and fracture mechanics.' *International Journal of Solids and Structures*, 49(15-16), pp. 2195-2201.

Rahimi, M., Blaber, A. P. and Menon, C. (2016) 'Towards the evaluation of force-sensing resistors for in situ measurements of interface pressure during leg compression therapy.' *In* Insititute of Electrical and Electronics Engineers. *Proceedings of 2016 IEEE Healthcare Innovation Point-of-Care Technologies Conference (HI-POCT)*, Cancun, Mexico, 9th – 11th November 2016. [Online] [Accessed on 21st May 2017] https://ieeexplore.ieee.org/abstract/document/7797688/

Rahi, S. (2017) 'Research design and methods: a systematic review of research paradigms, sampling issues and instruments development.' *International Journal of Economics and Management Sciences*, 6(2), pp. 1-5.

Ramanathan, R. (2008) *The Role of Organisational Change Management in Offshore Outsourcing of Information Technology Services*: *Qualitative Case Studies from a Multinational Pharmaceutical Company*. Ph.D. Florida Atlantic University. [Online] [Accessed on 20th September 2019].

Renstrom, P. A. F. H. (1993) 'Encyclopaedia of sports medicine. vol 4, Sports injuries: basic principles of prevention and care.' Blackwell scientific publications.

Rhodes, D. (2015) *How big will rugby players get?* 19th September. *The BBC*. [Online] [Accessed on 26th November 2019] https://www.bbc.co.uk/news/magazine-34290980.

Rijavec, T. and Bukosek, V. (2004) 'Novel fibres for the 21st century.' *Tekstilec*, 47(1/2), pp. 312-327.

Roberts, J., Jones, R., Harwood, C., Mitchell, S. and Rothberg, S. (2001) 'Human perceptions of sports equipment under playing conditions.' *Journal of Sports Sciences*, 19(7), pp. 485-497.

Roberts, S. P., Trewartha, G., England, M., Shaddick, G. and Stokes, K. A. (2013) 'Epidemiology of time-loss injuries in English community-level rugby union.' *Br Med J,* 3(11).

Rome, L. de. (2019) 'Could wearing motorcycle protective clothing compromise rider safety in hot weather?' *Accident Analysis and Prevention*, 128(2019), pp. 240-247.

Rosato, D. and Rosato, D. (2003) 'Design parameter.' *In* Rosato, D., and Rosato, D. (eds. *Plastics Engineered Product Design*. London: Elsevier Science, pp. 161-197.

Rule, R. J. (1981) 'Body protective pads.' US patent application: US4272850A.

Russell, K. M. (2004) 'On versus off the pitch: the transiency of body satisfaction among female rugby players, cricketers, and netballers.' *Sex Roles*, 51(2004), pp. 561-574.

Ryan, T. P. (2013) 'Sample size determination and power.' London: John Wiley and Sons.

Rylander, A. (2012) *Pragmatism and design research: an overview*. Stockholm: KTH Royal Institute of Technology.

Salkind, N. J. (2010) 'Encyclopedia of research design, volume 1.' London: SAGE.

Sallis, J. F., Conway, T. L., Prochaska, J. J., McKenzie, T. L., Marshall, S. L. and Brown, M. (2001) 'The association of school environments with youth physical activity.' *Am J Public Health*, 91(4), pp. 618-620.

Sanami, M., Alderson, A., Alderson, K. L., McDonald, S. a., Mottershead, B. and Withers, P. J. (2014a) 'The production and characterization of topologically and mechanically gradient open-cell thermoplastic foams.' *Smart Materials and Structures*, *23*(5), pp. 55016.

Sanami, M., Ravirala, N., Alderson, K. and Alderson, A. (2014b) 'Auxetic materials for sports applications.' *Procedia Engineering*, 72(2014), pp. 453-458.

Sanchez, A. J., Ruiz, E. C. V., Villalba, V. H. G. and Sanchez, M. R. F. (2020) 'Analysis of the approach to online advertising of leading sportswear brands.' *In* Margalina, V-M. and Lavin, J. M. (eds.) *Management and inter/intra organisational relationships in the textile and apparel industry*. PA: IGI Global, pp. 241-262.

Satterthwaite, P., Norton, R., Larmer, E. and Robinson, E. (1999) 'Risk factors for injuries and other health problems sustained in a marathon.' *Br J Sports Med*, 33(1999), pp. 22-26.

Schonheyder, J. F., and Nordby, K. (2018) 'The Use and Evolution of Design Methods in Professional Design Practice.' *Design Studies*, 58(2018), pp. 36-62.

Senthilkumar, M. and Kumar, A. (2012a) 'Design and Development of a Pressure Sensing Device for Analysing the Pressure Comfort of Elastic Garments.' *Fibers and Textiles in Eastern Europe*, 1(90), pp. 64-69.

Senthilkumar, M., Sounderraj, S. and Anbumani, N. (2012b) 'Effects of Spandex Input Tension, Spandex Linear Density and Cotton Yarn Loop Length on Dynamic Elastic Behaviour of Cotton/Spandex Knitted Fabrics.' *Journal of Textile and Apparel, Technology and Management*, 7(4), pp. 1-16.

Scarpa, F., Remilla, A. C., Landi, F. P. and Tomlinson, G. (2000) 'Damping modelization of auxetic foams.' *In* International society for optics and photonics. *SPIE's 7th annual international symposium on smart structures and materials*. Vol. 3989. Newport Beach, California, United States, 6th – 9th March. Varadan, V. V. (ed.).

Schneider, N. N., Michel, F. I., Vogt, K. and Emrich, F. (2019) 'Backpack impact protection in cycling – comparison of a conventional foam-based vs. an air-based protection system.' *Science and Cycling Congress*, 8(2), pp. 15-17.

Schoeman, R., Coetzee, D. and Schall, R. (2015) 'Positional tackle and collision rates in super rugby.' *International Journal of Performance Analysis in Sport*, 15(2015), pp. 1022-1036.

Schuren, J. (2014) 'In vitro measurements of compression bandages and bandage systems: a review of existing methods and recommendations for improvement.' *Veins and Lymphatics*, 3(1).

Schwab, K. (2017) 'The Fourth Industrial Revolution.' New York: Crown Business.

Sibal, A., Rawal, A. (2015) 'Design strategy for auxetic dual helix yarn systems.' *Materials Letters*, 161(2015), pp. 740-742.

Silverberg, J. L., Evans, A. A., McLeod, L., Hayward, R. C., Hull, T., Santangelo, C. D. and Cohen, I. (2014) 'Using origami design principles to fold reprogrammable mechanical metamaterials.' *Science*, 345(6197), pp. 647-650.

Sloan, M. R., Wright, J. R. and Evans, K. E. (2011) 'The helical auxetic yarn – a novel structure for composites and textiles; geometry, manufacture and mechanical properties.' *Mechanics of Materials*, 43(9), pp. 476-486.

Smith, F. C., Scarpa, F. and Burriesci, G. (2002) 'Simultaneous optimization of the electromagnetic and mechanical properties of honeycomb materials.' *In* International society for optics and photonics. *SPIE's 9th annual international symposium on smart structures and materials.* Vol. 4701. San Diego, California, United States, 17th – 21st March. Davis, L. P. (ed.)

Smith, L. J., Eichelberger, T. D. and Kane, E. J. (2018) 'Breast injuries in female collegiate basketball, soccer, softball and volleyball athletes: prevalence, type and impact on sports participation.' *Eur J Breast Health*, 14(1), pp. 46-50.

Spadoni, A. and Ruzzene, M. (2012) 'Elasto-static micropolar behavior of a chiral auxetic lattice.' *Journal of the mechanics and physics of solids*, 60(2012), pp. 156-171.

Sport England. (2020) Active Lives Adult Survey November 2018/19 Report. London, UK: UK Department of Health.

Staub, N. W., Lovu, T., Byrne, J. T., Murphy, K. A., Bernarding, M. P. and Ling, H. W. (2017) 'Protective apparel and methods of making the same.' US patent application: US20180099206A1.

Steffen, K., Anderson, T. E., Krosshaug, T., Mechelen, W. V., Myklebust, G., Verhagen, E. A. and Bahr, R. (2010) 'ECSS position statement 2009: prevention of acute sports injuries.' *European Journal of Sport Science*, 10(4), pp. 223-236.

Stolker, R. H. (2018) 'Protective lightweight helmet.' US patent application: US20190059494A1.

Story, D. A. and Tait, A. R. (2019) 'Survey research.' *Anesthesiology*, 130(2), pp. 192 – 202.

Strangewood, M. (2003) 'Modelling of materials for sports equipment.' *In* Subic, A. *(ed.) Materials In Sports Equipment.* Cambridge: Woodhead Publishing in Materials, pp. 3-33.

Stromnes, A. L. (1991) 'Dewey's view on knowledge and its educational implications. Critical considerations.' *Revista Espanola de Pedagogia*, 49(189), pp. 195-217.

Suh, M., Carroll, K. and Cassill, N. (2010) 'Critical review on smart clothing product development.' *Journal of Textile and Apparel Technology and Management,* 6(4), pp. 1-18.

Sun, L. and Zhao, L. (2017) 'Envisaging the era of 3D printing: a conceptual model for the fashion industry.' *Fashion and Textiles*, 4(1), pp. 1-16.

Sun, Y., Liu, X., Tian, G. and Han, H. (2012) 'Analysis of the D30 materials in baseball protective clothing.' *Applied Mechanics and Materials*, 217(2012), pp. 1174-1177.

Sun, Y., Xu, W., Wei, W., Ma, P. and Xia, F. (2019) 'Stab-resistance of auxetic weft-knitted fabric with kevlar fibers at quasi-static loading.' *Journal of Industrial Textiles.*

Sutter, G. W. and Cormier, S. M. (2012) 'Pragmatism: a practical philosophy for encironmental scientists.' *Integrated Environmental Assessment and Management*, 9(2), pp. 181-184.

Swain, M. S., Lystad, R. P., Henschke, N., Maher, C. G. and Kamper, S. J. (2016) 'Match injuries in amateur rugby union: a prospective cohort study.' *Chiropractic & Manual Therapies*, 24(17).

Sweeney, M. M. and Branson, D. H. (1990) 'Sensorial comfort: part I: a psychophysical method for assessing moisture sensation in clothing.' *Textile Research Journal*, 60(7), pp. 371-377.

Szafranska, H. and Korycki, R. (2020) ‘Analysis of mechanical properties of laminated seams.’ *Journal of Natural Fibers*, 17(3).

Talluri, S. (2006) ‘Multi-layered, impact absorbing, modular helmet.’ US patent application: US7089602B2.

Targett, S. G. (1998) ‘Injuries in professional rugby union.’ *Clin J Sport Med*, 8(4), pp. 280-285.

Taylor, M., Francesconi, L., Gerendas, M., Shanian, A., Carson, C. and Bertoldi, K. (2013) ‘Low porosity metallic periodic structures with negative Poisson’s ratio.’ *Advanced Materials,* 26(15), pp. 2365-2370.

Tharpe, R. B. and Costin, D. J. (2019) ‘System and method of generating a pattern or image on fabric with linear laser irradiation, fabric made by said method, and products made with said fabric.’ US patent application: US10450694B2.

Thomas, S. (2014) ‘Practical limitations of two devices used for the measurement of sub-bandage pressure: implications for clinical practice.’ *Journal of Wound Care*, 23(2014), pp. 300-313.

Timoshenko, S. and Goodier, J. N. (1970) ‘Theory of Elasticity.’ 3 ed., New York: McGraw-Hill.

Timothy, M. and Hupp, S. R. (2013) ‘Hot wedge welding machine and method of operation.’ US patent application: US9446555B2.

Tirloni, A. S., dos Reis, D. C., Dias, N. F. and Moro, A. R. R. (2018) ‘The use of personal protective equipment: finger temperatures and thermal sensation of workers’ exposure to cold environment.’ *Int J Environ Res Public Health,* 15(11).

Tong, Y. (2019) ‘Application of new materials in sports equipment.’ *IOP Conf. Ser.: Mater. Sci. Eng*, 493(1), pp. 1-4.

Toronjo, A. (2013) ‘Articles of apparel including auxetic materials.’ US patent application: 13838827.

Trewarth, G. and Stokes, K. (2003). ‘Impact forces during rugby tackles.’ *Proceedings of the international conference on the science and practice of rugby.* Brisbine, Australia, 5th – 7th November, pp. 5-7.

Troynikov, O. and Watson, C. (2015) ‘Knitting technology for seamless sportswear.’ *In* Shishoo, R. (ed.) *Textiles for Sportswear.* Victoria, Australia: Woodhouse Publishing. pp. 139-164.

Tsui, F. (2011) Determining impact intensities in contact sports. P.h.D. Loughborough University.

Tyler, D. and Venkatraman, P. D. (2011) ‘A critical review of impact resistant materials used in sportswear clothing.’ *7th International conference in advances in textiles, machinery, nonwovens and technical textiles*. India: Kumaraguru College of Technology Coimbatore, India, 15th – 17th December 2011. pp. 1-11. [Online] [Accessed on 10th September 2017] https://e-space.mmu.ac.uk/597115/1/ATNT%202011%20A%20critical%20review%20of%20impact%20resistant%20materials.pdf

Tyler, D. and Venkatraman, P. D. (2012) ‘Impact resistant materials and design principles for sportswear.’ *In* Textile Institute. *88th Textile Institute World Conference.* Malaysia, 15th – 17th May, pp. 2 - 21. [Online] [Accessed on 26th November 2019] https://e-space.mmu.ac.uk/597117/2/Tyler%2BVenkatraman_Impact-resistant-materials-for-sportswear.pdf

Ugbolue, S. C., Kim, Y. K., Warner, S. B., Fan, Q. and Yang, C. L. (2012) ‘Engineered warp knit auxetic fabrics.' *J Textile Sci Engg*, 2(1), pp. 1-8.

Uttam, D. (2013) 'Active Sportswear Fabrics.' *International Journal of IT, Engineering and Applied Sciences Research*, 2(1), pp. 34-40.

Venkatraman, P. D. (2016) 'Evaluating the performance of fabrics for sportswear.' *In* Hayes, S, G. and Venkatraman, P. (eds.) *Materials and technology for sportswear and performance apparel.* London: Taylor & Francis Group, pp. 262-286.

Venkatraman, P. D. and Tyler, D. (2016) 'Impact Resistant Materials and Their Potential.' *In* Hayes, S, G. and Venkatraman, P. (eds.) *Materials and technology for sportswear and performance apparel*. London: Taylor & Francis Group, pp. 205-230.

Wang, Z. and Hu, H. (2014) '3D auxetic warp-knitted spacer fabrics.' *Phys. Status Solidi B,* 251(2), pp. 281-288.

Watkins, S. M. (1995) *Clothing: the portable environment, 2nd ed*. Ames: Iowa State University Press.

Watkins, S. M. and Dunne, M. E. (2015) 'Commercial product development and production.' In *Functional clothing design,* London: *Bloomsbury publishing*, pp. 351-396.

Webster, J. M. and Roberts, J. (2009) 'Incorporating subjective end-user perceptions in the design process: a study of leg guard comfort in cricket.' *Proceedings of the Institute of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 223(2), pp. 49-62.

Whitty, J. P. M., Nazare, F. and Alderson, A. (2002) 'Modelling the effects of density variations on the in-plane Poisson's ratios and Young's moduli of periodic conventional and re-entrant honeycombs-part 1: rib thickness variations.' *Cellular polymers*, 21(2), pp. 69-98.

Williams, S., Trewartha, G., Kemp, S. and Stokes, K. (2013) 'A meta-analysis of injuries in senior men's professional rugby union.' *Sports Medicine*, 43(2013), pp. 1043-1055.

Wong, A. S. W., Li, Y. and Zhang, X. (2004) 'Influence of fabric mechanical property on clothing dynamic pressure distribution and pressure comfort on tight-fit sportswear.' *The Society of Fiber Science and Technology*, 60(10), pp. 293-299.

Wong, J., Gong, A. T., Defnet, P. A., Meabe, L., Beauchamp, B., Sweet, R. M., Sardon, H., Cobb, C. L. and Nelson, A. (2019) '3D printing Ionogel auxetic frameworks for stretchable sensors.' *Advanced Materials Technologies*, 4(19).

Wong, P. and Hong, Y. 'Soccer injury in the lower extremities.' *Br J Sports Med*, 39(2012), pp. 473-82.

World Health Organization. (2010) *Global recommendations on physical activity for health.* World health organisation. [Online] [Accessed 20th October 2018] https://www.who.int/dietphysicalactivity/global-PA-recs-2010.pdf

World Rugby. (2014) Rugby Ready. [Online] [Accessed on 10th February 2017] https://rugbyready.worldrugby.org/

World Rugby. (2015) *Game Analysis: Rugby World Cup 2015 Statistical Report*. 2015. [Online] [Accessed on 16th May 2017] https://resources.world.rugby/worldrugby/document/2015/12/17/4f81ca2f-a931-4d1f-aa1c-af37c68ef14a/151214_Rugby_World_Cup_2015_Statistcial_Report.pdf

World Rugby. (2016) *England Professional Rugby Injury Surveillance Project: 2015-2016 Season Report*. 2016. [Online] [Accessed on 27th June 2018] https://www.englandrugby.com/dxdam/96/960006d9-269d-4250-a15f-d9e62f8bfe70/PRISP_1516.pdf

World Rugby. (2018) *Year In Review*. Dublin, Ireland: World Rugby. [Online] [Accessed: 4th November 2020] http://publications.worldrugby.org/yearinreview2018/en/1-1/

World Rugby. (2019a) *Activate – A Structured Exercise Programme to Reduce Injuries in youth and Adult Community Rugby.* 2019. [Online] [Accessed: 22nd November 2019] https://iris.world.rugby/coaching/activate-injury-prevention-exercise-programme

World Rugby. (2019b) *Body Padding Performance Specification.* Dublin, Ireland: World Rugby. [Online] [Accessed 20 January 2020] https://playerwelfare.worldrugby.org/body-padding

Wright, J. R., Burns, M. K., James, E., Sloan, M. R. and Evans, K. E. (2012) 'On the design and characterisation of low-stiffness auxetic yarns and fabrics.' *Textile Research Journal*, 82(7), pp. 645-654.

Wu, W., Song, X., Liang, J., Xia, R., Qian, G. and Fang, D. (2018) 'Mechanical properties of anti-tetrachiral auxetic stents.' *Composite Structures*, 185(1), pp. 381-392.

Wyner, M. W., Cafaro, T., Garrard, R. L., Thorn, S. and Macrina, M. E. (2017) 'Breathable impact absorbing cushioning and constructions.' US patent application: US9615611B2.

Xu, W., Sun, Y., Lin, H., Wei, C., Ma, P. and Xia, F. (2019) 'Preparation of soft composite reinforced with auxetic warp-knitted spacer fabric for stab resistance.' *Textile Research Journal*, 90(3-4), pp. 323 – 332.

Yang, C-C., Ngo, T. and Tran, P. (2015) 'Influences of weaving architectures on the impact resistance of multi-layer fabrics.' *Materials & Design*, 85(2015), pp. 282-295.

Yang, D. U., Lee, S. and Huang, F. Y. (2003) 'Geometric effects on micropolar elastic honeycomb structure with negative Poisson's ratio using the finite element method.' *Finite Elements in Analysis and Design*, 39(3), pp. 187-205.

Yang, S., Qi, C., Guo, D. M. and Wang, D. (2011) 'Energy absorption of an re-entrant honeycombs with negative Poisson's ratio.' *Applied Mechanis and Materials*, 148-149, pp. 992-995.

Yang, S., Qi, C., Wang, D., Gao, R., Hu, H. and Shu, J. (2013) 'A comparative study of ballistic resistance of sandwich panels with aluminium foam and auxetic honeycomb cores.' *Advances in Mechanical Engineering*.

Yang, W., LI, Z., Shi, W., Xie, B. and Yang, M. (2004) 'Review of auxetic materials.' *Journal of materials science*, 39(2004), pp. 3269-3279.

Yao, Y. T., Alderson, K. L. and Alderson, A. (2016) 'Modelling of negative Poisson's ratio (auxetic) crystalline cellulose Iβ. Cellulose.' *Springer*, 23(6), pp. 3429-3448.

Yeh, H. P., Stone, J. A., Churchill, S. M., Brymer, E. and Davids, K. (2016) 'Physiological and emotional benefits of green physical activity: an ecological dynamics perspective.' *Sport Med*, 46(7), pp. 947-953.

Yeomans, C., Kenny, I. C., Cahalan, R., Warrington, G. D., Harrison, A. J., Hayes, K., Lyons, M., Campbell, M. J. and Comyns, T. M. (2018) 'The incidence of injury in amateur male rugby union: A systematic review and meta-analysis.' *Sports Med*, 48(2018), pp. 837-848.

Zakaria, N. (2014) 'Body shape analysis and identification of key dimensions for apparel sizing systems.' In *Anthropometry, Apparel Sizing and Design*, London: Woodhead Publishing Series in Textiles, pp. 95-119.

Zhang, C., Li, J., Hu, Z., Zhu, F. and Huang, Y. (2012) 'Correlation between the acoustic and porous cell morphology of polyurethane foam: Auxetics Creates effect of interconnected porosity.' *Materials and Design*, 41(2012), pp. 319-325.

Zhang, G., Ghita, O. R. and Evans, K. E. (2016) 'Dynamic thermo-mechanical and impact properties of helical auxetic yarns.' *Composites Part B: Engineering*, 99, pp. 494-505.

Zhao, S., Hu, H., and Kamrul, H., Chang, Y. and Zhang, M. (2019) 'Development of auxetic warp knitted fabrics based on reentrant geometry.' *Textile Research Journal*, 90(3-4), pp. 344-356.

Zhao, T. F., Deng, Z. C., Fu, C. Y., Wang, X. J., Zhou, H. Y. and Chen, C. Q. (2019) 'Thickness effect on mechanical behavior of auxetic sintered metal fiber sheets.' *Materials and Design*, 167(2019).

Zimmer, M. T., Kornas, A. T., Holland, A. J. and Poore, E. L. (2018) 'Technical swimwear with compression taping.' US patent application: US20190059465A1.

Zujiang, X. and Xu, W. (2014) 'High damping ethylene – vinyl acetate rubber foam shoe material and method.' Chinese patent application: CN104231419B.

Zuijang, X., Xu, W. and Ninqing, Z. (2014) 'Damping ethylene vinyl acetate rubber pange material for shoes high and preparation method thereof.' Chinese patent application: CN1042319B.

Zulifqar, A. and Hu, H. (2018) 'Development of bi-stretch auxetic woven fabrics based on re-entrant hexagonal geometry.' *Physica Status Solidi (b)*, 256(1).

Appendices

Appendix A. User Perceptions of Protective Rugby Apparel Survey Questions

Q1 What is your age? Answers: 18-24 years old (1); 25-34 years old (2); 35-44 years old (3); 45-54 years old (4); 55-64 years old (5); 65-74 years old (6); 75 years or older (7); Prefer not to answer (8)
Q2 What is your gender? Answers: Male (1); Female (2); Prefer not to answer (3)
Q3 What position do you play in rugby Union? Answers: Wing (1); Centre (2); Fly-half (3); Scrum-half (4); Number Eight (5); Flanker (6); Hooker (7); Prop (8); 2nd Row (9); Full-back (10)
Q4 What standard do you play rugby to? Answers: Recreational (1); Competitive (2); Semi-professional (3); Professional (4)
Q5 Do you wear a padded protective top during participation in rugby Union? Answers: Never (1); Sometimes (2), About half the time (3); Most of the time (4); Always (5)
Q6 Give a score of 1-5 of how far you feel that wearing a padded protective rugby top has helped to protect you against injury, where 5 is the highest level of protection. Answers refer to: Soft tissue damage (1); Lacerations (2); Disolcation (3); Breakage (4)
Q7 Does wearing a a padded protective rugby top affect the following during play? Where -2 indicates negativity, 0 is neutral and 2 has a positive effect on you during play. Choose N/A if you have never worn this garment. Answers refer to: Fit (1); Sensorial comfort (2); Thermal comfort (3); Aesthetics (4); Weight (5); Protection (6)
Q8 How heavily is your decision to wear or not to wear a padded protective rugby top influenced by the people around you? -2 shows that you have been discouraged,

0 is unaffacted by influence and 2 indicates that you have been encouraged to wear. Answers refer to: Team mates (1); Family (2); Coach (3)

Q9 Do you consider currently available padded protective rugby tops to meet your needs for the following factors? -2 does not meet this need, 0 is neutral and 2 meets the stated need. Choose N/A if you have never worn this garment and don't feel that you can comment. Answers refer to: Fit (1); Sensorial comfort (2); Thermal comfort (3); Protection (4); Aesthetics (5); Weight (6)

Q10 If you were to buy a padded protective rugby top or have in the past, what would be the most important factor that would influence your decision to purchase it? Number each item in importance where 1 is the most important. Ranked orders: Thermal Comfort (1); Weight/bulkyness (2); Aesthetics (3); Sensorial comfort (feel) (4); Protection (5); Fit (6)

Appendix B.

Confidence and parametric assumptions:

1. Training levels with PPE wear: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .032$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

2. Positions with PPE wear: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .220$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

3. Age with PPE wear: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .370$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

4. Gender with PPE wear: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test ($p = .002$) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Mann-Whitney test has been selected for further analysis of this study.

5. Training levels with injury – soft tissue damage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .449$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

6. Training levels with injury – lacerations: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .829$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

7. Training levels with injury – dislocation: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normally distributed. In addition, the Levene's test ($p = .470$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

8. Training levels with injury – breakage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .759) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

9. Positions with injury – soft tissue damage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .263) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

10. Positions with injury – lacerations: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .854) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

11. Positions with injury – dislocation: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .478) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

12. Positions with injury – breakage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .296) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

13. Age with injury – soft tissue damage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .934) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

14. Age with injury – lacerations: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .197) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

15. Age with injury – dislocation: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .191) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

16. Age with injury – breakage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .159) showed the data was homogenous;

hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

17. Gender with injury – soft tissue: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .291$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

18. Gender with injury – lacerations: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .911$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

19. Gender with injury – dislocation: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .559$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

20. Gender with injury – breakage: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .892$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

21. Training levels with Encouragement – teammates: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .160$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

22. Training levels with Encouragement – family: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test ($p = .040$) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

23. Training levels with Encouragement – coach: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .271$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

24. Positions with Encouragement – team mates: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .111$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

25. Positions with Encouragement – family: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .009) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

26. Positions with Encouragement – coach: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .181) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

27. Age with Encouragement – teammates: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .041) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

28. Age with Encouragement – family: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .036) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

29. Age with Encouragement – Coach: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .005) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

30. Gender with Encouragement – team mates: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .979) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

31. Gender with Encouragement – family: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .430) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

32. Gender with Encouragement – coach: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .987) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

33. Training levels with Affect on comfort – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .293) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

34. Training levels with Affect on comfort – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .013) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non- parametric Kruskall Wallace test has been selected for further analysis of this study.

35. Training levels with Affect on comfort – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .457) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

36. Training levels with Affect on comfort – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .149) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

37. Training levels with Affect on comfort – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .075) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

38. Training levels with Affect on comfort – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .430) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

39. Positions with Affect on comfort –fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .714) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

40. Positions with Affect on comfort – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .757) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

41. Positions with Affect on comfort – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .683) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

42. Positions with Affect on comfort – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .138$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

43. Positions with Affect on comfort – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .654$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

44. Positions with Affect on comfort – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .875$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

45. Age with Affect on comfort – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .573$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

46. Age with Affect on comfort – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .936$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

47. Age with Affect on comfort – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .950) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

48. Age with Affect on comfort – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .592) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

49. Age with Affect on comfort – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .976) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

50. Age with Affect on comfort – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .004) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

51. Gender with Affect on comfort – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .996) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

52. Gender with Affect on comfort – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .555) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

53. Gender with Affect on comfort – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .037) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Mann Whitney has been selected for further analysis of this study.

54. Gender with Affect on comfort – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .003) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Mann Whitney has been selected for further analysis of this study.

55. Gender with Affect on comfort – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .238) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

56. Gender with Affect on comfort – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .644) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

57. Training levels with comfort needs – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .664) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

58. Training levels with comfort needs – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .983) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

59. Training levels with comfort needs – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test ($p = .015$) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

60. Training levels with comfort needs – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .102$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

61. Training levels with comfort needs – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .077$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

62. Training levels with comfort needs – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .125$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

63. Positions with comfort needs – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test ($p = .395$) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

64. Positions with comfort needs – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .199) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

65. Positions with comfort needs – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .403) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

66. Positions with comfort needs – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .098) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

67. Positions with comfort needs – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .723) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

68. Positions with comfort needs – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .850) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

69. Age with comfort needs – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .190) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

69. Age with comfort needs – Sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .839) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

70. Age with comfort needs – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .289) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

71. Age with comfort needs – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .087) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

72. Age with comfort needs – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .882) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

73. Age with comfort needs – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .814) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

74. Gender with comfort needs – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .080) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

75. Gender with comfort needs – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .317) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

76. Gender with comfort needs – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .196) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

77. Gender with comfort needs – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .864) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

78. Gender with comfort needs – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .673) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

79. Gender with comfort needs – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .906) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

80. Training level with purchase influence – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .083) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

81. Training level with purchase influence – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .754) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

81. Training level with purchase influence – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .000) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallcae test has been selected for further analysis of this study.

82. Training level with purchase influence – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .995) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

83. Training level with purchase influence – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .106) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

84. Training level with purchase influence – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .900) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

85. Positions with purchase influence – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .005) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

86. Positions with purchase influence – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .627) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

87. Positions with purchase influence – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .603) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

88. Positions with purchase influence – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .998) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

89. Positions with purchase influence – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .561) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

90. Positions with purchase influence – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .728) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

91. Age with purchase influence – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .575) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

92. Age with purchase influence – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .427) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

93. Age with purchase influence – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .643) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

94. Age with purchase influence – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .055) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

95. Age with purchase influence – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .164) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric ANOVA test has been selected for further analysis of this study.

96. Age with purchase influence – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .023) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Kruskall Wallace test has been selected for further analysis of this study.

97. Gender with purchase influence – thermal comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .560) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

98. Gender with purchase influence – weight: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .381) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

99. Gender with purchase influence – aesthetics: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .373) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

100. Gender with purchase influence – sensorial comfort: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .339) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

101. Gender with purchase influence – protection: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. However, the Levene's test (p = .004) showed the data was heterogeneous; hence the data has not been found to meet the parametric assumptions and a non-parametric Mann Whitney test has been selected for further analysis of this study.

102. Gender with purchase influence – fit: The mean values for each group falls within the 95% confidence interval range of means, indicating that we can have confidence in this sample. An assessment of the Q-Q plots determined the data to be approximately normal. In addition, the Levene's test (p = .134) showed the data was homogenous; hence the data has been found to meet the parametric assumptions and a parametric t-test has been selected for further analysis of this study.

Appendix C. Significance Tests

1. PPE and Training levels: The result of the Kruskal-Wallis test (*H(2) = 2.18, p = .337*) is not statistically significant. Therefore the null hypothesis is accepted.

2. PPE and Playing positions: The result of the Kruskal-Wallis test (*H(2) = .92, p = .63*) is not statistically significant. Therefore the null hypothesis is accepted.

3. PPE and Age: The result of the Kruskal-Wallis test (*H(2) = 1.43, p = .49*) is not statistically significant. Therefore the null hypothesis is accepted.

4. PPE and Gender: Mann-Whitney: Choice to wear PPE during participation in rugby did not differ significantly (*U = 1711.50, p = .21)* between men (mean rank = 70.98) and women (mean rank = 62.74). Therefore the null hypothesis is accepted.

5. Protection against injury and Training levels: The result of ANOVA test indicates that there was no significant difference in participants training levels influencing their beliefs in the protectiveness of PPE (*soft tissue damage: F = 2.21, df = 2, p = .12*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*lacerations: H(2) = .19, p = .91, dislocation: H(2) = 1.19, p = .55, breakage: H(2) = .74, p = .69*) is not statistically significant. Therefore the null hypothesis is accepted.

6. Protection against injury and Playing positions: The result of ANOVA test indicates that there was no significant difference in participants playing positions influencing their beliefs in the protectiveness of PPE (*soft tissue damage: F = .19, df = 2, p = .82; lacerations: F = .15, df = 2, p = .86*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*Dislocation: H(2) = .03, p = .99, breakage: H(2) = .02, p = .99*) is not statistically significant. Therefore the null hypothesis is accepted.

7. Protection against injury and Age: The result of ANOVA test indicates that there was no significant difference in participants age groups influencing their beliefs in the protectiveness of PPE (*soft tissue damage: F = 1.20, df = 2, p = .31; lacerations: F = .43, df = 2, p = .65*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*Dislocation: H(2) = 2.59, p = .*27, *breakage: H(2) = .70, p = .70*) is not statistically significant. Therefore the null hypothesis is accepted.

8. Protection against injury and Gender: The result of the t-test test (*lacerations: mean male = 2.81, mean female = 3.05, t = - .68, df = 70, p = .50*) is not statistically significant at 0.05 level. Therefore, the null hypothesis is accepted, as the findings from this study do not provide enough evidence to conclude that rugby participant' opinions of the protectiveness against lacerations of PPE differs by gender. Mann-Whitney: Perceptions of the ability for PPE to protect against particular injuries did not differ significantly (*soft tissue: U = 549.00, p = .65; dislocation: U = 427.50, p = .93; breakage: U = 430.00, p = .43*) between men (mean rank: soft tissue = 38.30; dislocation = 34.62; breakage = 35.46) and women (mean rank: soft tissue = 40.86; dislocation = 34.15; breakage = 39.61). Therefore the null hypothesis is accepted.

9. Encouragement to wear PPE and Training levels: The result of the Kruskal-Wallis test (*teammates: H(2) = 6.57, p = .04, family: H(2) = 2.35, p = .31, coach: H(2) = 3.46, p = .18*) indicates that statistical significance has been found between training levels and encouragement from teammates. Therefore the null hypothesis is rejected for teammates.

Further analysis by pairwise comparison tests found statistical differences in how far rugby participants' feel they have been encouraged or discouraged to wear PPE by other people between two out of three training levels. A statistically significant difference (p = .03) in influence from teammates members having encouraged rugby players to wear PPE was found in those of a competitive level (mean rank = 781.73) and players of a professional level (mean rank = 46.67). There were no statistically significant differences found between participants of a recreational playing level with competitive (p = 1.00) or professional players (p = .12).

10. Encouragement to wear PPE and Playing positions: The result of the Kruskal-Wallis test (*team mates: H(2) = 1.76, p = .42, family: H(2) = 2.92, p = .23, coach: H(2) = .17, p = .92*) is not statistically significant. Therefore the null hypothesis is accepted.

11. Encouragement to wear PPE and Age: The result of the Kruskal-Wallis test (*teammates: H(2) = 3.88, p = .14, family: H(2) = 7.88, p = .02, coaches: H(2) = 3.02, p = .22*) found a statistically significant difference between age groups and influence from family to wear PPE. We therefore reject the null hypothesis. Further analysis by pairwise comparison tests found statistical differences in how far rugby participants' feel they have been encouraged or discouraged to wear PPE by other people between two out of three age categories. A statistically significant difference (p = .02) in influence from family members having encouraged rugby players to wear PPE was found in those aged 18 – 24 years (mean rank = 78.35) and players of 35 + years (mean rank = 54.08). There were no statistically significant differences found between participants aged 25 – 34 years with those aged 18 – 24 (p = .29) or 35+ years (p = .33).

12. Encouragement to wear PPE and Gender: The result of the t-test test (*teammates: mean male = - .18, mean female = - .07, t = - .57, df = 134, p = .57*) is not statistically significant at 0.05 level. Therefore, the null hypothesis is accepted, as the findings from this study do not provide enough evidence to conclude that influence to wear PPE from teammates differs by gender. Mann-Whitney: Encouragement to wear PPE experienced by the participants did not differ significantly (*family: U = 1905, p = .82; coaches: U = 1791, p = .34*) between men (mean rank: family = 68.05; coaches = 66.85) and women (mean rank: family = 69.54; coaches = 72.32). Therefore the null hypothesis is accepted.

13. Comfort during rugby and Training levels: The result of the Kruskal-Wallis test (*fit: H(2) = 2.69, p = .26, sensorial comfort: H(2) = .62, p = .73, thermal comfort: H(2) = 3.60, p = .17, aesthetics: H(2) = 1.43, p = .49, weight: H(2) = .38, p = .83, protection: H(2) = .58, p = .75*) is not statistically significant. Therefore the null hypothesis is accepted.

14. Comfort during rugby and Playing positions: The result of ANOVA test indicates that there was no significant difference in how participants of different playing levels experience the comfort of their PPE (*fit: F = .83, df = 2, p = .44; thermal comfort: F = .98, df = 2, p = .38; sensorial comfort: F = 2.82, df = 2, p = .07*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*aesthetics: H(2) = 1.54, p = .46, weight: H(2) = .30, p = .86, protection: H(2) = .81, p = .67*) is not statistically significant. Therefore the null hypothesis is accepted.

15. Comfort during rugby and Age: The result of ANOVA test indicates that there was no significant difference in how participants of different age groups experience the comfort of their PPE (*fit: F = 1.57, df = 2, p = .22; weight: F = 1.55, df = 2, p = .22; sensorial comfort: F = .75, df = 2, p = .48*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*thermal: H(2) = .14, p = .93, aesthetics: H(2) = 1.37, p = .51, protection: H(2) = .53, p = .77*) is not statistically significant. Therefore the null hypothesis is accepted.

16. Comfort during rugby and Gender: Mann-Whitney: Participants perceived affect of PPE on their comfort did not differ significantly (fit: *U = 517.5, p = .15; sensorial comfort: U = 550.5, p = .17; thermal comfort: U = 660, p = .51; aesthetics: U = 621.5, p = .57; weight: U = 733, p = .80; protection: U = 682.5, p = .30*) between men (mean rank: fit = 45.04; sensorial comfort = 45.53; thermal comfort = 43.50; aesthetics = 42.21; weight = 44.61; protection = 48.11) and women (mean rank: fit = 36.38; sensorial comfort = 37.21; thermal comfort = 47.50; aesthetics = 45.40; weight = 46.13; protection = 41.67). Therefore the null hypothesis is accepted.

17. Comfort requirements and Training levels: The result of the Kruskal-Wallis test (*fit: H(2) = 1.58, p = .46; sensorial comfort: H(2) = 3.26, p = .20; protection: H(2) = 4.64, p = .10; aesthetics: H(2) = 7.07, p = .03; thermal comfort: H(2) = .75, p = .69, weight: H(2) = .55, p = .76*) found a statistically significant difference between training levels and perceptions of the aesthetic quality of PPE. Therefore the null hypothesis is rejected. Further analysis by pairwise comparison tests found statistical differences in rugby participants' perceptions of the aesthetic quality of currently available PPE across two out of three training level categories. A statistically significant difference (p = .02) in perceptions of PPE aesthetics was found in competitive players (mean rank = 50.55) compared with those training at a recreational (mean rank = 31.17). There were no statistically significant differences found in perceptions of PPE aesthetics between rugby players training at a professional and recreational level (p = .31) or competitive level (p = 1.00).

18. Comfort requirements and Playing positions: The result of the ANOVA test indicates that there was no significant difference in how participants of different playing positions find PPE to meet their comfort needs (*fit: F = .89, df = 2, p = .41; sensorial comfort: F = .14, df = 2, p = .87; thermal comfort: F = .25, df = 2, p = .78*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*protection: H(2) = .73, p = .69; aesthetics: H(2) = 1.92, p = .38; weight: H(2) = 1.98, p = .37*) is not statistically significant. Therefore the null hypothesis is accepted.

19. Comfort requirements and Age: The result of ANOVA test indicates that there was no significant difference in how participants of different age groups find PPE to meet their comfort needs (*fit: $F = 1.50$, $df = 2$, $p = .23$; thermal comfort: $F = .49$, $df = 2$, $p = .62$*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (*sensorial comfort: $H(2) = 1.23$, $p = .54$; protection: $H(2) = 1.64$, $p = .44$; aesthetics: $H(2) = 1.85$, $p = .40$; weight: $H(2) = .85$, $p = .65$*) is not statistically significant. Therefore the null hypothesis is accepted.

20. Comfort requirements and Gender: The result of the t-test test (*thermal comfort: mean male = - .37, mean female = - .37, $t = .01$, $df = 93$, $p = .99$; aesthetics: mean male = - .12, mean female = - .44, $t = 1.34$, $df = 91$, $p = .18$; weight: mean male = .12, mean female = - .04, $t = .57$, $df = 92$, $p = .57$*) was not statistically significant. We therefore reject the null hypothesis. Mann-Whitney: Statistical significance between the perceptions of how far PPE meets participants comfort requirements was found (fit: *$U = 1293$, $p < .01$*, sensorial comfort: *$U = 770.5$, $p = .25$*, protection: *$U = 728.5$, $p = .18$*) between men (mean rank: fit = 74.74, sensorial comfort = 49.50, protection = 48.79) and women (mean rank: fit = 52.54, sensorial comfort = 42.54, protection = 40.98). Therefore the null hypothesis is rejected. The findings of this study provide evidence to conclude that women find PPE significantly more uncomfortable than men through the fit of the garment specifically.

21. Purchase of PPE and Training level: The result of ANOVA test indicates that there was no significant difference in how participants of different training levels will prioritise different realms of comfort (*thermal comfort: $F = 2.14$, $df = 2$, $p = .12$; weight: $F = .17$, $df = 2$, $p = .85$; sensorial comfort: $F = 1.11$, $df = 2$, $p = .33$; fit: $F = 1.41$, $df = 2$, $p = .25$*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (aesthetics: *$H(2) = 5.71$, $p = .06$, protection: $H(2) = 1.11$, $p = .58$*) is not statistically significant. Therefore the null hypothesis is accepted.

22. Purchase of PPE and Playing positions: The result of ANOVA test indicates that there was no significant difference in how participants of different playing positions will prioritise different realms of comfort (*weight: $F = .16$, $df = 2$, $p = .85$; sensorial* *comfort: F = 1.50, df = 2, p = .23*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (thermal comfort: *H(2) = 1.74, p = .42, aesthetics: H(2) = 1.72, p = .42, protection: H(2) = 4.36, p = .11, fit: H(2) = 1.11, p = .57*) is not statistically significant. Therefore the null hypothesis is accepted.

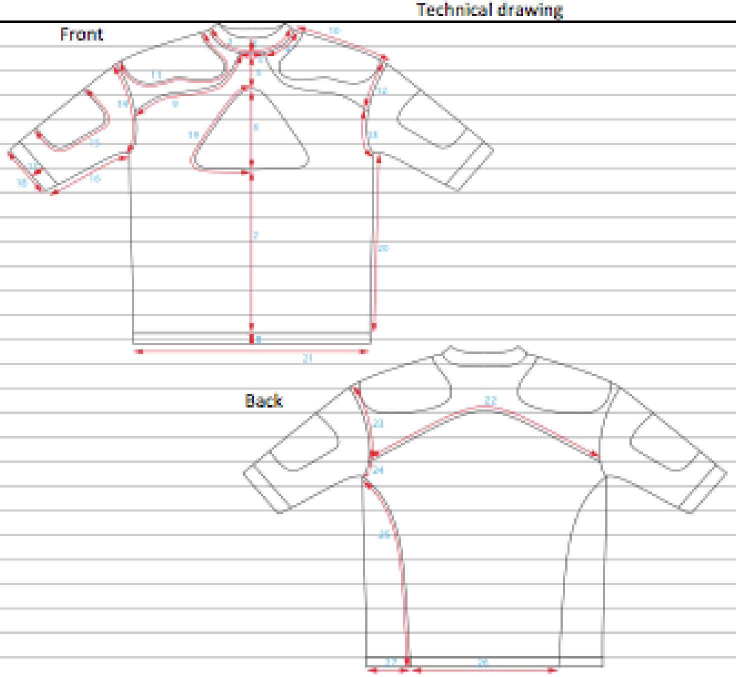
23. Purchase of PPE and Age: The result of ANOVA test indicates that there was no significant difference in how participants of different playing positions will prioritise different realms of comfort (*thermal comfort: F = .01, df = 2, p = .99; weight: F = 1.32, df = 2, p = .27; protection: F = .06, df = 2, p = .95*). Therefore, the null hypothesis is accepted. The result of the Kruskal-Wallis test (fit: *H(2) = 2.73, p = .26, aesthetics: H(2) = 2.82, p = .24, sensorial comfort: H(2) = .40, p = .82*) is not statistically significant. Therefore the null hypothesis is accepted.

24. Purchase of PPE and Gender: The result of the t-test test (*thermal: mean male = 3.56, mean female = 3.63, t = - .23, df = 126, p = .82; weight: mean male = 3.65, mean female = 3.63, t = .08, df = 126, p = .94; sensorial comfort: mean male = 3.49, mean female = 4.00, t = - 1.91, df = 126, p = .06*) was not statistically significant at 0.05 level. We therefore accept the null hypothesis. Mann-Whitney: Opinions of how far protection influences the purchase of PPE did not differ significantly (fit: *U = 1633, p = .50*, aesthetics: *U = 1458.5, p = .09*, protection: *U = 1440, p = .07*) between men (mean rank: fit = 65.94, aesthetics = 61.07, protection = 68.14) and women (mean rank: fit = 61.33, aesthetics = 72.04, protection = 56.50). Therefore the null hypothesis is accepted.

Appendix D: Pilot Study

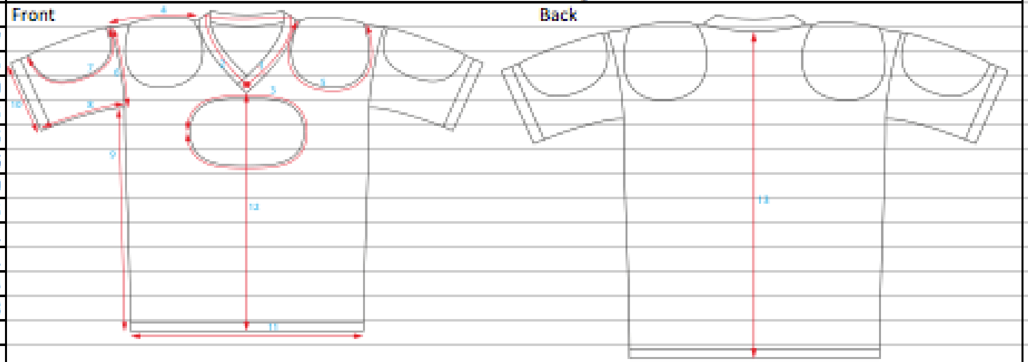
1. Kooga – Measurement Chart

Measurement chart			
No.	Position on garment	Measurment (cm)	Technical drawing
1	Centre front neck panel depth	3	
2	Total neckline	46.5	
3	Front body panel neck edge	5.8	
4	Front shoulder panel neck edge	9.5	
5	neck edge to chest pad vertical measurement	8.3	
6	Chest pad depth (vertical)	17	
7	Chest pad to waist line vertical measurement	38.2	
8	Waist hem depth	2	
9	Front shoulder panel lower edge	26.5	
10	Shoulder seam	21	
11	Shoulder pad circumference	73.2	
12	Front shoulder panel over arm edge	30	
13	Front body panel U/A edge	11.1	
14	Total sleeve U/A edge	45.8	
15	Sleeve pad circumference	56	
16	Inside arm	21.4	
17	Sleeve cuff depth	3	
18	Arm hole	27	
19	Chest pad circumference (on the half)	31.5	
20	side seam	43.5	
21	Waist line (on the half)	47.8	
22	Across back curve (horizontal)	53.5	
23	Back shoulder panel over arm edge	17.5	
24	Back panel U/A edge	6.5	
25	Back panel S/S	45.3	
26	Back panel waist line	27.8	
27	Back side panel waist line	12	



2. Optimum Tribal Five Pad – Measurement Chart

Measurement chart			
No.	Position on garment	Measurement (cm)	Technical Drawing
1	Neck cuff depth	2.5	
2	Neckline	57	
3	Chest pad circumference	60.5	
4	Shoulder seam	19	
5	Shoulder pad circumference	80.5	
6	U/A seam	39.6	
7	Arm pad circumference	56	
8	Inside arm	19	
9	S/S	50.5	
10	Arm hole	31	
11	Waist (on the half)	41	
12	CF depth (vertical)	54.4	
13	CB depth (vertical)	65.8	

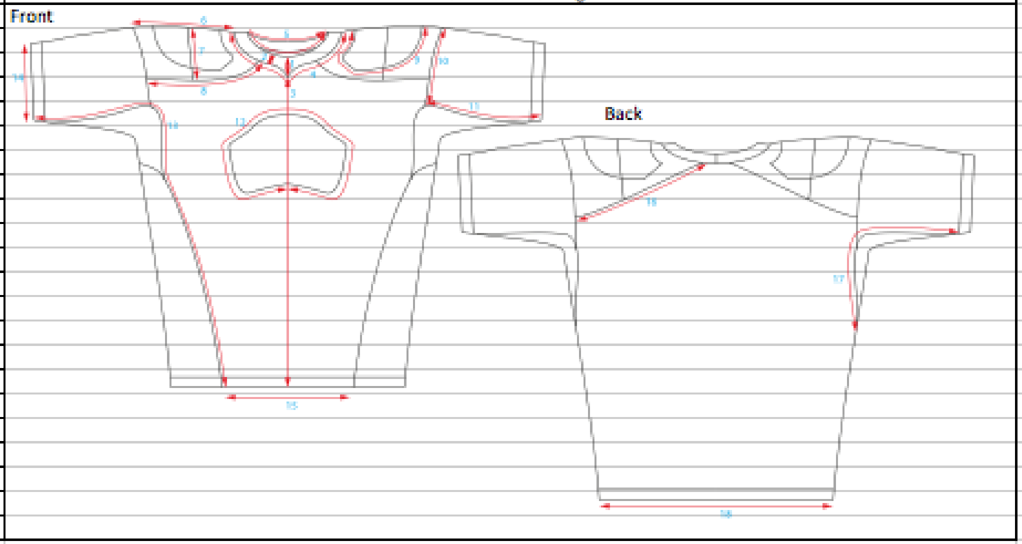


3. Canterbury Raze – Measurement Chart

Measurement chart

No.	Position on garment	Measurement (cm)
1	CF cuff depth	5
2	cuff depth around neck	2
3	CF depth	58
4	Neckline lower edge	46.8
5	Neckline higher edge (of cuff)	37
6	Length of horizontal stitching on shoulder pad segment	25
7	Length of vertical stitching on shoulder pad segment	25
8	Shoulder panel front horizontal edge	24
9	Total circumference of shoulder pads	59.5
10	Over arm seam	26.2
11	Inside arm seam	23.4
12	Circumference of chest pad	50.5
13	S/S	84.4
14	Arm hole	31.6
15	Front panel waist line	22.4
16	Back shoulder panel lower edge	28.2
17	U/A panel back side seam	27.5
18	Back panel waistline	74

Technical Drawing

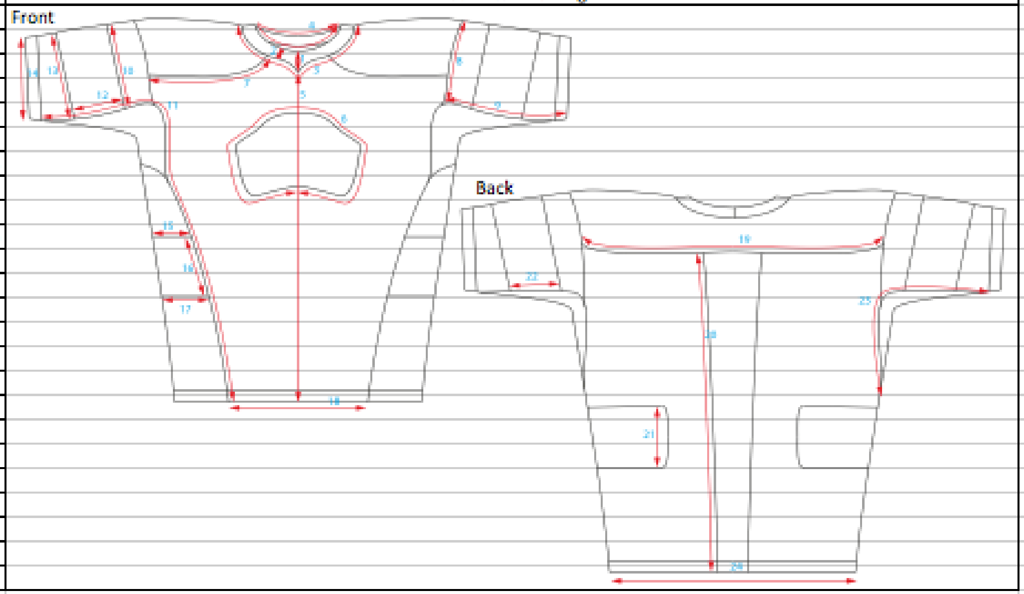


4. Canterbury Raze Pro – Measurement Chart

Measurement chart

No.	Position on garment	Measurement (cm)
1	CF cuff depth	5
2	cuff depth around neck	2
3	Neckline lower edge	46.8
4	Neckline higher edge (of cuff)	37
5	CF depth	58
6	Circumference of chest pad	50.5
7	Shoulder panel front horizontal edge	24
8	Over arm seam	26.2
9	Inside arm seam	21.4
10	Higher horizontal length of arm pad	16
11	S/S	82.4
12	Front side edge of arm pad	9
13	Lower horizontal length of arm pad	16.1
14	Arm hole	31.6
15	Higher horizontal edge of hip pad	24.5
16	Front side edge of hip pad	10.8
17	Lower horizontal edge of hip pad	25.5
18	Front panel waist line	24.5
19	Back shoulder panel lower edge	52.6
20	CB panel S/S	54.6
21	Back side edge of hip pad	11.3
22	Back side edge of arm pad	7.8
23	U/A panel back side seam	29
24	Back panel waistline	67

Technical Drawing



5. Gilbert Triflex XP1 - Construction Method

Construction method			
No.	Machine	S/A (cm)	Operation
1	Heat Press	-	Heat seal Shoulder padding to shoulder panel
2	C/S	1	Seal edge of shoulder padding
3	L/S	0.3	Lay chest pad cover on the front body panel and attach along the curved edge
4	L/S	0.3	Insert front chest pad and close the upper edge
5	C/S	1	Seal raw edge of chest pad cover
6	L/S	1	Secure centre line of arm padding to sleeve
7	L/S	0.3	Place padding either side of centre line and close edges
8	C/S	1	Seal raw edge of padding cover
6	L/S	0.3	Lay chest pad cover on the back body panel and attach along the curved edge
7	L/S	0.3	Insert front chest pad and close the upper edge
8	C/S	1	Seal raw edge of back pad cover
9	O/L	0.6	Attach lower back panel to centre back panel
10	L/S	0.3	Top stitch the lower back panel seam flat.
11	O/L	0.6	Join side panels to front chest panel and higher back panel
12	C/S	1	Lay the seams flat and seal
13	O/L	0.6	Join front body panel to the side panel and chest panel, repeat for back panel
14	C/S	1	Lay seams flat and seal
15	O/L	0.6	Join over shoulder seam
16	O/L	0.6	Join inside arm seam
17	O/L	0.6	Join lower edge of shoulder and under arm panel to upper edge of main body
18	C/S	1	Turn the seam up and seal
19	L/S	0.6	Bag out centre front neck panel within outer neck panel along the side seams
20	O/L	0.6	Join neck panel lower edge to neck line of shoulder panel
21	O/L	0.6	Close the sleeve cuff at the side seam
22	L/S	0.6	Fold cuff over and tack edges
23	O/L	0.6	Join sleeve cuff to arm hole of the sleeve
24	C/S	2	Turn up the waistline hem by 2cm and secure

6. Kooga – Construction Method

Construction method			
No.	Machine	S/A (cm)	Operation
1	-	-	Mould foam design to nylon lycra
2	O/L	0.6	Join shoulder seam
3	L/S	0.3	Tack join the shoulder pad to the shoulder panel
4	C/S	1	Seal shoulder pad edge
5	L/S	0.3	Tack join front pad cover to wrong side of front body panel, overlapping the centre vertical edges by 3cm
6	C/S	1	Seal edge of front pad cover
7	Hand	-	Insert front pad inside pocket.
8	L/S	0.3	Tack join back pad cover to wrong side of back body panel, overlapping the centre vertical edges by 3cm
9	C/S	1	Seal edge of back pad cover
10	Hand	-	Insert back pad inside pocket
11	L/S	0.3	Tack join arm pad cover to wrong side of arm body panel, overlapping the centre vertical edges by 3cm
12	C/S	1	Seal edge of arm pad cover
13	Hand	-	Insert arm pad inside pocket.
14	O/L	0.6	Join shoulder panel to front and back body panels
15	O/L	0.6	Join both side panels to the back body panel.
16	O/L	0.6	Join sleeve to body panels at the arm hole
17	O/L	0.6	Join the S/S including the inside arm seam and the front body panel S/S
18	O/L	0.6	Join S/S of neck cuff and fold so that the raw edges meet and the wrong sides are facing.
19	O/L	0.6	Join neck cuff to neckline of body panel
20	O/L	0.6	Join S/S of sleeve cuff and fold so that the raw edges meet and the wrong sides are facing.
21	O/L	0.6	Join sleeve cuff to arm hole of sleeve panel
22	T/N C/S	2	Turn up waist hem by 2cm

7. Optimum Tribal Five Pad – Construction Method

Construction method			
No.	Machine	S/A (cm)	Operation
1	O/L	0.6	Join shoulder seam
2	T/N C/S	1	Overlap shoulder pad covers at centre opening by 4cm and join edge to shoulder
3	Hand	-	Insert shoulder pad into cover
4	T/N C/S	1	Overlap front pad covers at centre opening by 4cm and join edge to front body panel
5	Hand	-	Insert chest pad into cover
6	T/N C/S	1	Overlap back pad covers at centre opening by 4cm and join edge to back panel
7	Hand	-	Insert back pad into cover
8	T/N C/S	1	Overlap arm pad covers at centre opening by 4cm and join edge to sleeve
9	Hand	-	Insert arm pad into cover
10	O/L	0.6	Join arm hole seam
11	O/L	0.6	Join S/S along the inside arm and front and back body panels
12	O/L	0.6	Fold neck cuff so that wrong sides are facing and join to neckline, overlapping into a V shape at the CF
13	L/S	0.6	Join S/S of sleeve cuffs and fold so that wrong sides are facing
14	O/L	0.6	Join the two raw edges of the cuff to the sleeve
15	T/N C/S	2	Turn up the hemline

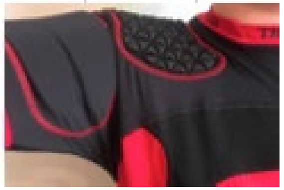
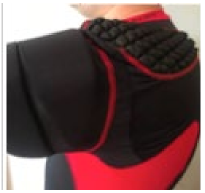
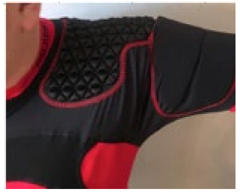
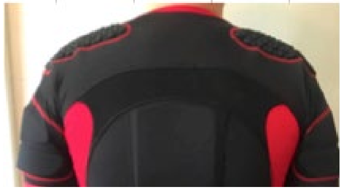
8. Canterbury Raze – Construction Method

Construction method			
No.	Machine	S/A (cm)	Operation
1	T/N C/S	-	Layer the two shoulder panel pieces sand join with two intersecting, perpendicular lines of stitching.
2	Hand	-	Insert the four pads between the two shoulder panel fabric layers and between the lines of stitching.
3	L/S	-	Close the segments of all four shoulder pads.
4	O/L	0.6	Seal centre edge of both chest pad cover pieces
5	L/S	0.3	Overlap centre edges of the two pieces and seal overlap by 5cm into each side
6	L/S	0.6	Seal raw edge of cover
7	T/N C/S	1	Join cover to wrong side of front panel
8	Hand	-	Insert chest pad
9	O/L	0.8	Join shoulder panel to front and back panel
10	T/N C/S	1	Seal across shoulder back and front seams
11	O/L	0.8	Join sleeve over arm seam
12	O/L	0.8	Join U/A to back and sleeve
13	C/S	1	Seal U/A join to back panel and sleeve
14	O/L	0.8	Join front S/S
15	C/S	1	Seal front S/S (body to sleeve)
16	O/L	0.8	Join neck cuff S/S and fold
17	O/L	0.8	Join neck cuff to neckline
18	T/N C/S	2	Turn up sleeve hem and seal
19	C/S	2	Turn up waist hem and seal

9. Canterbury Raze Pro - Construction Method

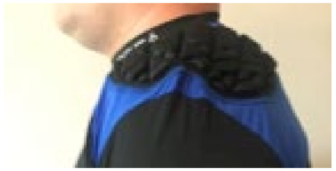
Construction method			
No.	Machine	S/A (cm)	Operation
1	O/L	0.8	Seal centre edge of both chest pad cover pieces
2	L/S	0.3	Overlap centre edges of the two pieces and seal overlap by 5cm into each side
3	O/L	0.6	Seal raw edge of cover
4	T/N C/S	-	Join cover to wrong side of front panel
5	Hand	-	Insert pad
6	O/L	0.8	Seal centre edge of both hip pad cover pieces
7	L/S	0.3	Overlap centre edges of the two pieces and seal overlap by 5cm into each side
8	C/S	-	Join outside vertical edge of hip pad cover to body
9	C/S	-	Join horizontal edges of hip pad cover to body on inside
10	Hand	-	Insert pad
11	O/L	0.8	Seal centre edge of both arm pad cover pieces
12	L/S	0.3	Overlap centre edges of the two pieces and seal overlap by 5cm into each side
13	C/S	-	Join outside vertical edge of arm pad cover to sleeve
14	C/S	-	Join horizontal edges of arm pad cover to sleeve on inside
15	Hand	-	Insert pad
16	Hand	-	Sandwich foam between shoulder panels and tack using adhesive
17	O/L	0.8	Join shoulder panel to front body
18	T/N C/S	-	Turn down seam and seal
19	O/L	0.8	Join CB panel sides
20	C/S	-	Seal CB panel both S/S
21	O/L	0.8	Join sleeve over arm seam
22	O/L	0.8	Join U/A to back panel and sleeve
23	C/S	-	Seal seam
24	O/L	0.8	Join front S/S
25	C/S	-	Seal front S/S
26	O/L	0.6	Join S/S of neck cuff
27	L/S	0.6	Join neckline to cuff
28	O/L	0.6	Seal raw neckline edge
29	O/L	0.6	Fold sleeve cuff so that wrong sides are facing
30	O/L	0.8	Join sleeve to arm cuff
31	T/N C/S	1	Turn back arm cuff and seal onto sleeve
32	C/S	2	Turn up waist hem

Fit Images and Comments:

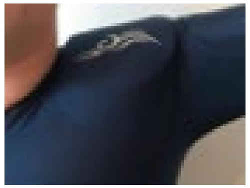
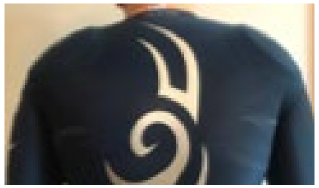
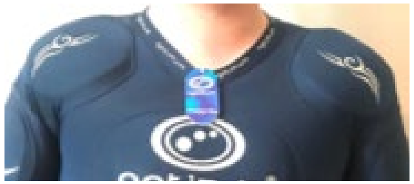
10. Gilbert Triflex XP1: 1.  **2.**  **3.**  **4.**  **5.** 

General Comments - The shoulder and arm protective padding both cover a larger surface area than the four other protective garments analysed in this study. As such, pictures 1, 2 and 3 indicate that when the arm is raised, the separate pads come into contact and overlap. Picture 2 also shows that where the shoulder pad and arm pad meet, the shoulder pad curls under itself slightly. The cause of this may be excessive material gathering at the shoulder and upper arm, which is evident in images 5 and 6. Although the excessive material offers the wearer an improved mobility and comfort it does not encourage the pads to conform to the body in a relaxed position or during movement. A poor fit and excessive material may also enable the pads to move or slide during a collision/impact. Pictures 4 and 5 indicate that despite the design including segmenting and contouring around the shoulder, the large surface area of the shoulder pad does not conform to the shoulder even in a relaxed state, which is evident due to the folding of at various points around the edge of the pad.

11. Kooga: 1.  **2.**  **3.**  **4.** 

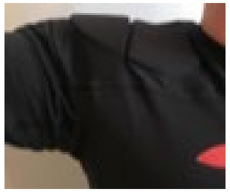
5. 

General Comments - The fit of the garment is taught to the model's body and as such this has allowed the pads to conform better to the shoulder. This is effective in both a relaxed position shown in 3, 4 and 5 as well as a raised arm position in 1 and 2. The success of the design is also due to the shape of the contour which effectively mimics the shape of the collar bone, it may also relate to the segmenting technique which utilises smaller cells at regions of the shoulder pad which are required to be more flexible such as toward the edges of the pad. However, excess material gathers at the shoulder, which is shown in image 5. The gathering is caused where the rigidity of the pad restricts the stretch of the main body fabric it has been stitched on to, which in turn causes the surrounding fabric to pull uncomfortably. This is always going to be an issue where a rigid pad is stitched directly on to a close fitting stretch garment. Whilst the pad shape conforms well to the shoulder, there is slight folding seen in picture 5.

12. Optimum: 1.  **2.**  **3.**  **4.**  **5.** 

General Comments - The fit of this garment is much tighter than the other four garments, and as such it is too small for the model. Because the pads have been embedded rather than stitched down on to the garment, there is no gathering of fabric surrounding the pad when the body is in a relaxed position and therefore the pad doesn't restrict the stretch of the main body of fabric in the same way that the other garments in this study do. Although images 2 and 3 show slight gathering of fabric between the shoulder and arm pad where the arm is raised, which shows that the rigidity of the pad does restrict the stretch and relaxation of the fabric which will affect the pressure comfort of the garment. Where the arm is raised in image 2 and 3, it is obvious that by not using any method of segmentation, the flexing of the shoulder is not able to be mimicked by the shoulder pad, and therefore suggests a lack of comfort relating to flexibility and bulk. The inward curve at the shoulder joint and neckline of the shoulder pad allow for some flexibility when the arm is raised, which in turn shortens the space between the neck and the shoulder joint. The garment utilises traditional tailoring seams rather than sportswear seams, therefore it includes seams that run at the under arm (side seam and inside arm) as well as the shoulder seam, these seams are overlocked rather than flat seamed which could cause friction during activity.

13. Canterbury Raze: 1.



2.

3.

4.

5.

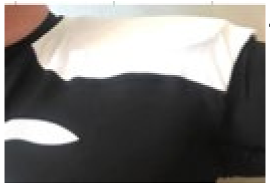
General Comments - The top is a comfortable fit on the model. Picture 5 shows that even when the model is in a relaxed position, there is a lot of gathering around the shoulder pads, this is because the fabric is not stretched over the rigid shoulder pad and then the surrounding fabric at the shoulder pulls in excess in order to compensate for the lack of stretch at the regions of padded protection. Images 1, 2, 3 and 4 show that the segmentation of the pads allow them to conform well to shoulder movements, despite these designs utilising a simpler method of segmentation. The excess gathering of fabric at the shoulder is pulling under the wearer's arm, which may cause discomfort during wear through excess bulk and folding of the fabric. The garment utilises sportswear seams such as including an under arm panel and the side seam positioning toward the front of the body.

14. Canterbery Raze Pro: 1.

2.

3.

4.



5.

General Comments - Overall the garment appears to be well fitted to the model. Image 3 shows that the side back panels are pulling at the side seam of centre back panel, indicating that the fabric utilised for the centre back panel has a higher stretch than that of the side back panels. Image 2 and 4 show that the segmented design of the shoulder pad conforms well to the body during movement. Images 4 and 5 shows that there is some excess fabric at the shoulder/under arm seam but this is minimal and may have been included to increase comfort by preventing restriction otherwise caused by wearing protective pads. The rigid pads have some flexibility due to the laser cut segments, the cut out effect may also improve breathability.

Appendix E: Fit of the Nine Commercial Shoulder Pads

1. Participant 1

Pads	Shoulder Padding		Surrounding Fabric	General Fit		
	Splaying	Bunching	Pulling	F Shoulder	B Shoulder	Chest
A	No	No	F, B	Loose	Taught	Taught
B	No	No	F, B	Loose	Taught	Taught
C	Yes	Yes	F, B	Taught	Taught	Taught
D	Yes	No	F, B	Loose	Loose	Loose
E	Yes	No	F, B	Loose	Loose	Loose
F	No	Yes	F, B	Loose	Loose	Loose
G	No	No	F, B	Loose	Taught	Taught
H	Yes	No	F, B	Tight	Tight	Tight
I	Yes	No	F, B	Loose	Tight	Tight

A.

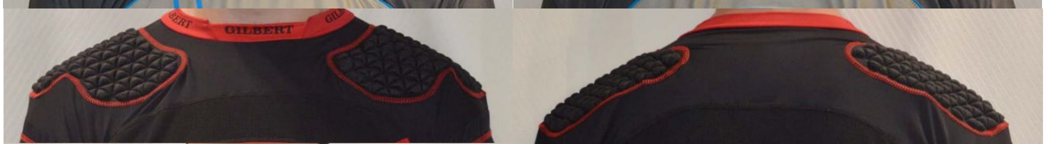
B.

C.

D.

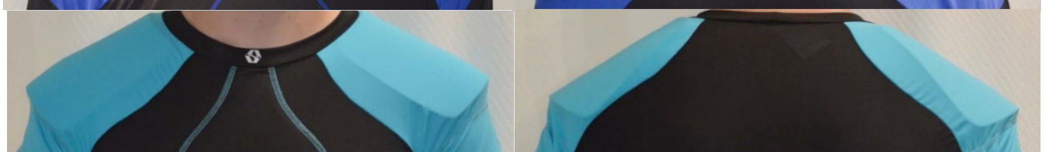
E.

F.



G.

H.



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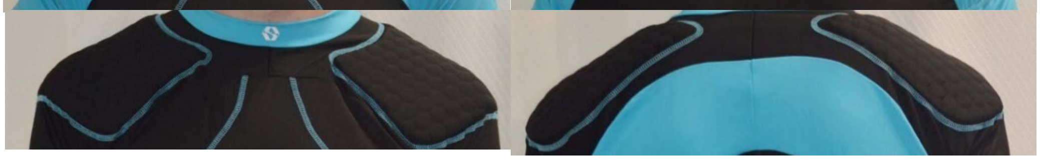


Pressure Comfort Measurements

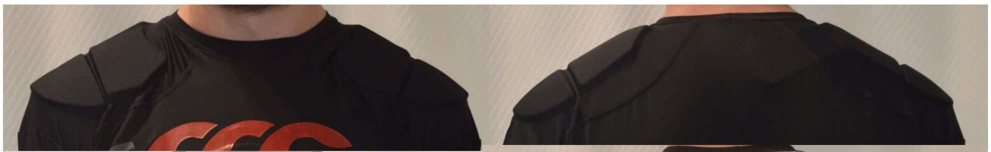
1. Participant 1

Picopress Measurement mmHg Tests 1, 2 and 3										
Garment and body position			Front				Back			
			1	2	3	Mean	1	2	3	Mean
	A. Canterbury Vapodri Raze	Position 1	6	4	5	5	4	4	4	4
		Position 2	2	2	2	2	0	1	2	1
		Position 3	1	1	2	1.3	1	1	1	1
		Position 4	2	1	1	1.3	1	1	1	1
	Canterbury Vapodri Raze pro	Position 1	4	6	7	5.7	2	3	5	3.3
		Position 2	1	1	2	1.3	0	0	0	0
		Position 3	1	0	0	0.3	0	1	0	0.3
		Position 4	5	3	3	3.7	0	0	0	0
	Gilbert Triflex Match V3	Position 1	3	4	6	4.3	0	1	3	1.3
		Position 2	3	2	3	2.7	0	0	0	0
		Position 3	1	0	1	0.7	0	0	0	0
		Position 4	2	1	1	1.3	1	1	1	1
	Gilbert Chieftain V3	Position 1	6	8	11	8.3	2	0	0	0.7
		Position 2	0	0	1	0.3	1	0	0	0.3
		Position 3	0	0	0	0	0	0	0	0
		Position 4	1	1	0	0.7	0	0	0	0
	Gilbert Atomic Zenon	Position 1	1	0	0	0.3	2	1	1	1.3
		Position 2	1	0	0	0.3	0	0	0	0
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Triflex XP1	Position 1	4	4	5	4.3	1	0	1	0.7
		Position 2	3	4	4	3.7	1	0	1	0.7
		Position 3	0	0	0	0	1	0	1	0.7
		Position 4	2	4	2	2.7	0	0	1	0.3
	Kooga IPS V	Position 1	5	3	3	3.7	1	1	1	1
		Position 2	1	1	2	1.3	0	0	0	0
		Position 3	1	1	1	1	1	1	1	1
		Position 4	2	1	1	1.3	0	0	0	0
	Body Armour Tech Vest BA	Position 1	2	4	3	3	2	4	5	3.7
		Position 2	0	2	0	0.7	0	0	0	0
		Position 3	0	1	0	0.3	0	0	0	0
		Position 4	6	6	7	6.3	0	0	0	0
	Body Armour Flexitop BA	Position 1	0	0	0	0	5	3	4	4
		Position 2	0	0	0	0	1	0	1	0.7
		Position 3	0	0	0	0	3	4	5	4
		Position 4	0	0	3	1	0	0	0	0

2. Participant 2

Pads	Shoulder Padding		Surrounding Fabric	General Fit		
	Splaying	Bunching	Pulling	F Shoulder	B Shoulder	Chest
A	No	No	F, B	Loose	Taught	Taught
B	No	No	F, B	Loose	Taught	Taught
C	Yes	Yes	F, B	Taught	Taught	Taught
D	Yes	No	F, B	Loose	Loose	Loose
E	Yes	No	F, B	Loose	Loose	Loose
F	No	Yes	F, B	Loose	Loose	Loose
G	No	No	F, B	Loose	Taught	Taught
H	Yes	No	F, B	Tight	Tight	Tight
I	Yes	No	F, B	Loose	Tight	Tight

A.



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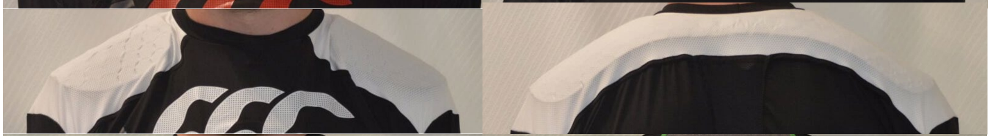

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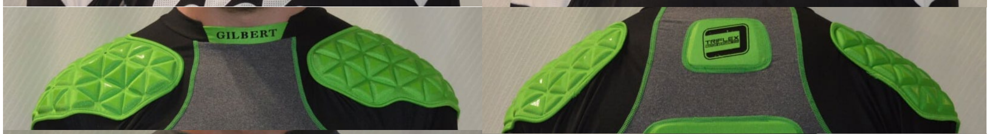
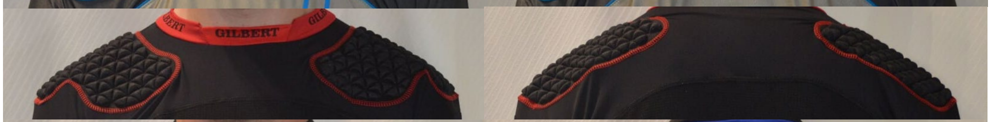


D.

E.

F.



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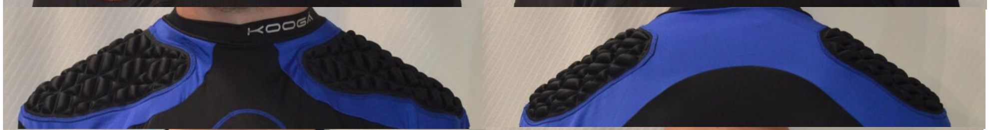

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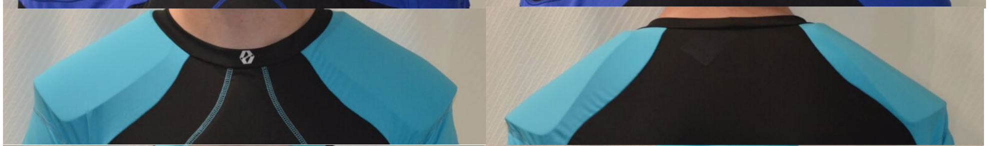

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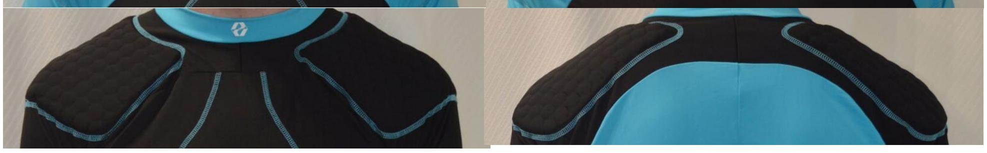


2. Participant 2

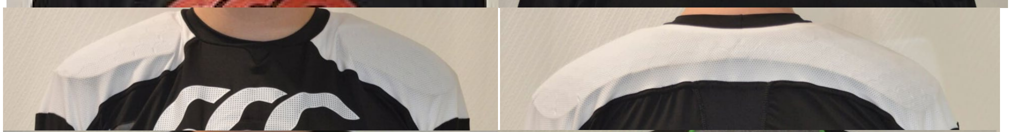
Picopress Measurement mmHg Tests 1, 2 and 3										
Garment and body position			Front				Back			
			1	2	3	Mean	1	2	3	Mean
	Canterbury Vapodri Raze	Position 1	0	2	2	1.3	2	1	2	1.7
		Position 2	3	3	3	3	2	1	2	1.7
		Position 3	1	1	1	1	1	1	1	1
		Position 4	6	4	6	5.3	0	0	0	0
	Canterbury Vapodri Raze pro	Position 1	4	1	1	1	3	4	3	3.3
		Position 2	1	0	1	0.7	1	1	1	1
		Position 3	1	0	1	0.7	1	0	1	0.7
		Position 4	4	1	3	2.7	0	0	0	0
	Gilbert Triflex Match V3	Position 1	0	1	1	0.7	1	2	2	1.7
		Position 2	0	1	1	0.7	0	0	0	0
		Position 3	0	0	0	0	1	1	1	1
		Position 4	1	3	3	2.3	1	1	1	1
	Gilbert Chieftain V3	Position 1	0	0	0	0	0	0	0	0
		Position 2	0	0	0	0	0	0	0	0
		Position 3	0	0	0	0	1	0	1	0.7
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Atomic Zenon	Position 1	0	0	0	0	1	1	1	1
		Position 2	1	0	1	0.7	0	0	0	0
		Position 3	0	0	0	0	1	0	1	0.7
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Triflex XP1	Position 1	0	0	0	0	0	0	0	0
		Position 2	1	1	1	1	0	0	0	0
		Position 3	1	1	1	1	0	0	0	0
		Position 4	0	5	5	3.3	0	0	0	0
	Kooga IPS V	Position 1	2	0	2	1.3	1	0	1	0.7
		Position 2	0	1	1	0.7	0	0	0	0
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	1	1	0.7	0	0	0	0
	Body Armour Tech Vest BA	Position 1	1	1	1	1	1	1	1	1
		Position 2	0	0	0	0	0	0	0	0
		Position 3	0	0	0	0	1	1	1	1
		Position 4	5	4	4	4.3	0	0	0	0
	Body Armour Flexitop BA	Position 1	1	0	1	0.7	1	1	1	1
		Position 2	1	0	1	0.7	0	0	0	0
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0

3. Participant 3

Pads	Shoulder Padding		Surrounding Fabric	General Fit		
	Splaying	Bunching	Pulling	F Shoulder	B Shoulder	Chest
A	No	No	F, B	Loose	Taught	Tight
B	No	No	F, B	Loose	Taught	Taught
C	Yes	Yes	F, B	Tight	Tight	Tight
D	Yes	No	F, B	Loose	Loose	Loose
E	Yes	No	F, B	Loose	Loose	Loose
F	Yes	Yes	F, B	Loose	Loose	Loose
G	No	No	F, B	Loose	Loose	Taught
H	Yes	No	F, B	Tight	Tight	Tight
I	Yes	No	F, B	Loose	Tight	Tight

A.

B.

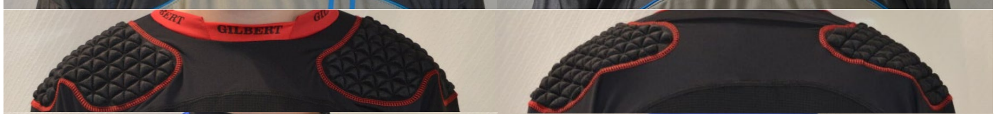


C.

D.

E.

F.



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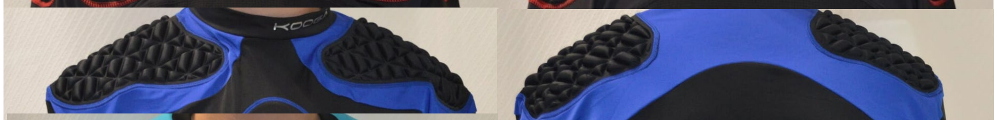

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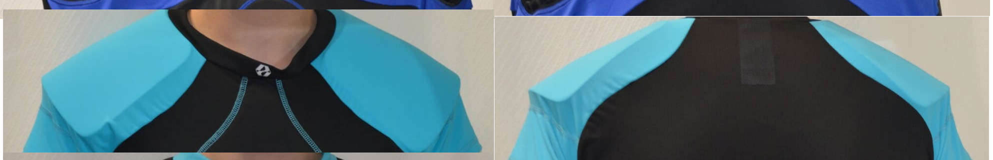

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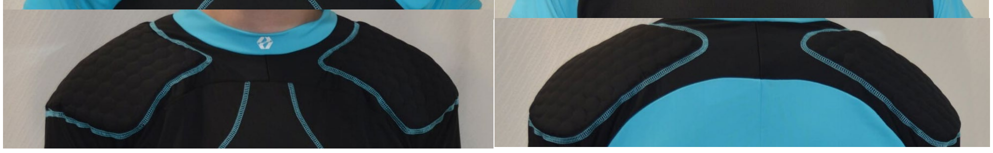

3. Participant 3

Picopress Measurement mmHg Tests 1, 2 and 3										
Garment and body position			Front				Back			
			1	2	3	Mean	1	2	3	Mean
	Canterbury Vapodri Raze	Position 1	1	1	1	1	3	5	5	4.3
		Position 2	0	0	0	0	1	4	4	3
		Position 3	3	0	2	1.7	0	1	1	0.7
		Position 4	1	1	1	1	0	0	0	0
	Canterbury Vapodri Raze pro	Position 1	5	1	4	3.3	3	3	3	3
		Position 2	0	0	0	0	1	1	1	1
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	1	1	0.7	0	0	0	0
	Gilbert Triflex Match V3	Position 1	0	3	3	2	1	2	2	1.7
		Position 2	0	0	0	0	1	1	1	1
		Position 3	0	1	1	0.7	0	1	1	0.7
		Position 4	8	7	8	7.7	0	0	0	0
	Gilbert Chieftain V3	Position 1	1	0	1	0.7	0	0	0	0
		Position 2	0	0	0	0	1	2	2	1.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	2	3	3	2.7	0	0	0	0
	Gilbert Atomic Zenon	Position 1	0	1	1	0.7	1	0	1	0.7
		Position 2	1	0	1	0.7	1	0	1	0.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	1	0	1	0.7	0	0	0	0
	Gilbert Triflex XP1	Position 1	1	0	1	0.7	1	0	1	0.7
		Position 2	0	0	0	0	1	1	1	1
		Position 3	1	1	1	1	0	0	0	0
		Position 4	1	1	1	1	0	0	0	0
	Kooga IPS V	Position 1	1	1	1	1	2	2	2	2
		Position 2	0	0	0	0	1	0	1	0.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	1	2	2	1.7	0	0	0	0
	Body Armour Tech Vest BA	Position 1	0	0	0	0	2	2	2	2
		Position 2	0	0	0	0	1	1	1	1
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0
	Body Armour Flexitop BA	Position 1	0	0	0	0	2	2	2	2
		Position 2	0	0	0	0	1	0	1	0.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0

4. Participant 4

Pads	Shoulder Padding		Surrounding Fabric	General Fit		
	Splaying	Bunching	Pulling	F Shoulder	B Shoulder	Chest
A	No	No	F, B	Loose	Taught	Tight
B	No	No	F, B	Taught	Taught	Taught
C	Yes	Yes	F, B	Tight	Tight	Tight
D	Yes	No	F, B	Loose	Loose	Loose
E	Yes	No	F, B	Loose	Loose	Loose
F	Yes	Yes	F, B	Loose	Loose	Loose
G	No	No	B	Tight	Taught	Taught
H	Yes	No	F, B	Tight	Tight	Tight
I	No	No	F, B	Tight	Tight	Tight

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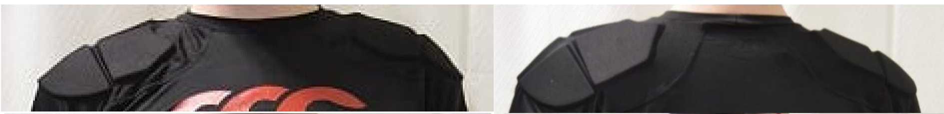

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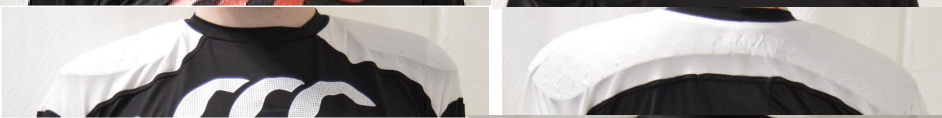

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D.

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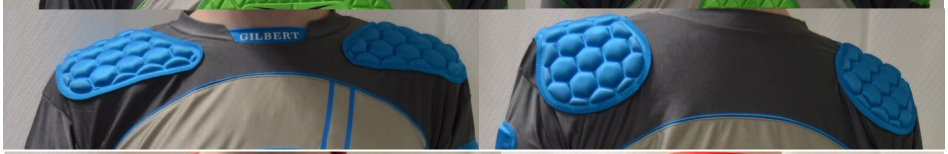

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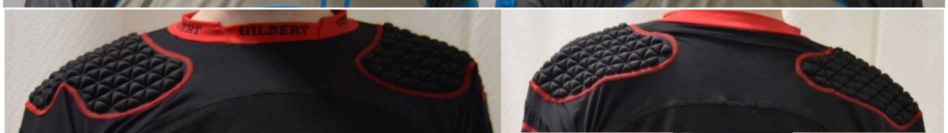

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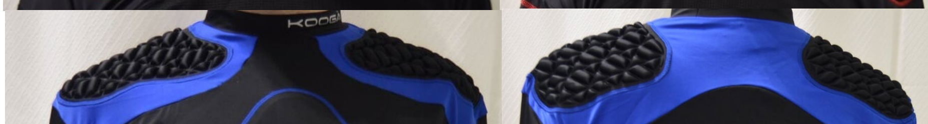

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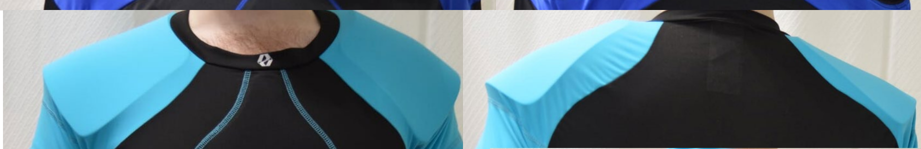

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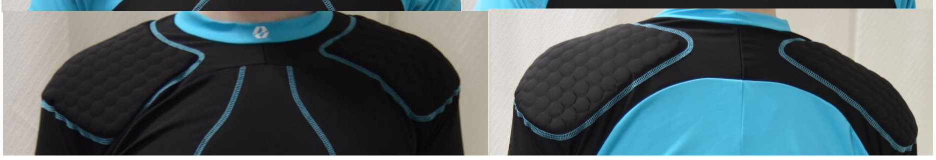


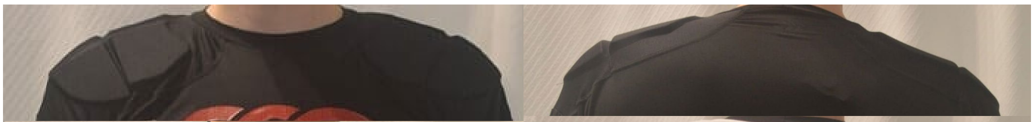
4. Participant 4

Picopress Measurement mmHg Tests 1, 2 and 3										
			Front				Back			
			1	2	3	Mean	1	2	3	Mean
Garment and body position	Canterbury Vapodri Raze	Position 1	0	0	1	0.3	2	2	2	2
		Position 2	1	1	0	0.7	3	2	2	2.3
		Position 3	5	1	2	2.7	1	1	1	1
		Position 4	3	1	4	2.7	0	1	1	0.7
	Canterbury Vapodri Raze pro	Position 1	3	3	2	2.7	4	4	3	3.7
		Position 2	1	1	1	1	2	2	2	2
		Position 3	0	0	0	0	1	1	1	1
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Triflex Match V3	Position 1	0	0	0	0	1	1	1	1
		Position 2	0	0	0	0	6	4	4	4.7
		Position 3	0	0	0	0	1	1	1	1
		Position 4	0	0	0	0	1	1	1	1
	Gilbert Chieftain V3	Position 1	0	0	0	0	1	1	1	1
		Position 2	1	1	0	0.7	1	1	1	1
		Position 3	1	1	1	1	1	1	0	0.7
		Position 4	1	1	2	1.3	0	0	0	0
	Gilbert Atomic Zenon	Position 1	0	0	0	0	1	1	0	0.7
		Position 2	1	0	1	0.7	2	2	3	2.3
		Position 3	1	1	1	1	0	0	0	0
		Position 4	2	2	2	2	0	0	0	0
	Gilbert Triflex XP1	Position 1	1	1	1	1	1	1	1	1
		Position 2	0	1	1	0.7	3	3	3	3
		Position 3	1	1	1	1	0	0	0	0
		Position 4	2	2	2	2	0	0	0	0
	Kooga IPS V	Position 1	0	0	0	0	2	2	1	1.7
		Position 2	0	0	0	0	3	3	3	3
		Position 3	5	4	4	4.3	1	1	2	1.3
		Position 4	12	11	10	11	0	0	0	0
	Body Armour Tech Vest BA	Position 1	0	0	0	0	1	1	1	1
		Position 2	0	0	0	0	2	2	1	1.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0
	Body Armour Flexitop BA	Position 1	0	0	0	0	2	2	1	1.7
		Position 2	0	0	0	0	3	3	2	2.7
		Position 3	0	0	0	0	1	1	1	1
		Position 4	0	0	0	0	0	0	0	0

5. Participant 5

Pads	Shoulder Padding		Surrounding Fabric	General Fit		
	Splaying	Bunching	Bunching	F Shoulder	B Shoulder	Chest
A	No	No	F, B	Loose	Tight	Tight
B	No	No	F	Loose	Tight	Taught
C	Yes	Yes	F	Tight	Tight	Tight
D	Yes	No	F, B	Loose	Loose	Loose
E	Yes	No	F, B	Loose	Taught	Loose
F	No	Yes	F, B	Loose	Taught	Loose
G	No	No	F	Taught	Tight	Tight
H	Yes	No	No	Tight	Tight	Tight
I	No	No	F	Tight	Tight	Tight

A.



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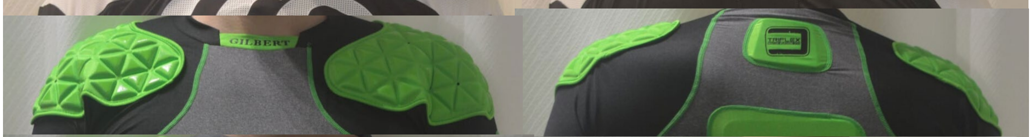

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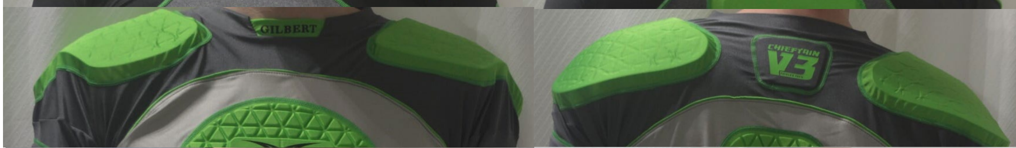

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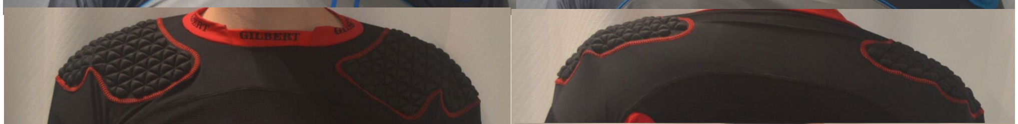

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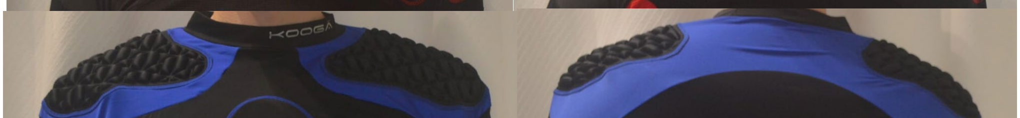

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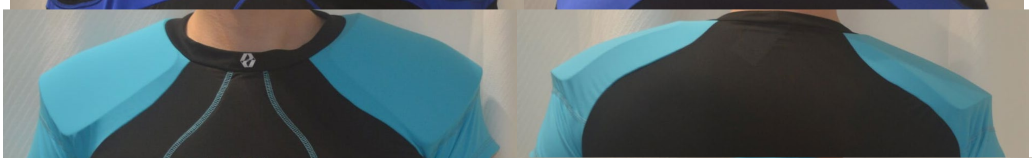

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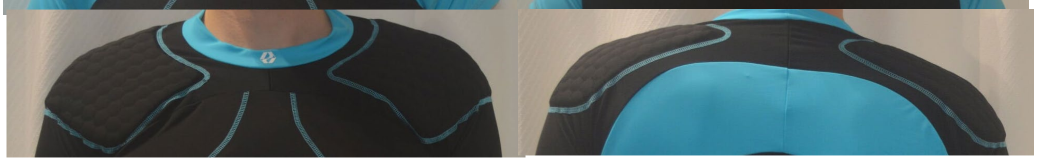


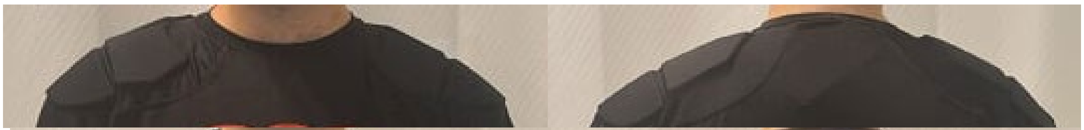
5. Participant 5

Picopress Measurement mmHg Tests 1, 2 and 3										
Garment and body position			Front				Back			
			1	2	3	Mean	1	2	3	Mean
	Canterbury Vapodri Raze	Position 1	1	1	1	1	10	6	6	7.3
		Position 2	1	1	1	1	2	2	2	2
		Position 3	7	6	6	6.3	1	1	1	1
		Position 4	7	7	7	7	1	1	1	1
	Canterbury Vapodri Raze pro	Position 1	7	7	5	6.3	5	5	6	5.3
		Position 2	0	0	0	0	2	2	2	2
		Position 3	2	2	3	2.3	2	2	2	2
		Position 4	5	5	4	4.7	1	1	1	1
	Gilbert Triflex Match V3	Position 1	0	0	0	0	7	7	8	7.3
		Position 2	6	5	6	5.7	1	1	1	1
		Position 3	1	1	1	1	5	5	5	5
		Position 4	0	0	0	0	4	4	4	4
	Gilbert Chieftain V3	Position 1	2	2	2	2	3	3	3	3
		Position 2	0	0	0	0	5	5	4	4.7
		Position 3	0	0	0	0	2	2	2	2
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Atomic Zenon	Position 1	0	0	0	0	3	3	3	3
		Position 2	5	5	4	4.7	1	1	1	1
		Position 3	3	3	3	3	1	1	1	1
		Position 4	1	1	1	1	1	1	1	1
	Gilbert Triflex XP1	Position 1	0	0	0	0	6	6	5	5.7
		Position 2	3	3	3	3	1	1	1	1
		Position 3	4	4	3	3.7	1	1	1	1
		Position 4	1	1	1	1	0	0	0	0
	Kooga IPS V	Position 1	2	2	2	2	7	7	6	6.7
		Position 2	0	0	0	0	3	3	3	3
		Position 3	2	2	2	2	2	2	2	2
		Position 4	5	5	4	4.7	0	0	0	0
	Body Armour Tech Vest BA	Position 1	0	0	0	0	4	4	3	3.7
		Position 2	0	0	0	0	2	2	2	2
		Position 3	3	3	3	3	0	0	0	0
		Position 4	2	2	2	2	0	0	0	0
	Body Armour Flexitop BA	Position 1	0	0	0	0	6	6	5	5.7
		Position 2	0	0	0	0	5	5	5	5
		Position 3	0	0	0	0	2	2	2	2
		Position 4	0	0	0	0	0	0	0	0

6. Participant 6

Pads	Shoulder Padding		Surrounding Fabric	General Fit		
	Splaying	Bunching	Bunching	F Shoulder	B Shoulder	Chest
A	No	No	F, B	Loose	Taught	Tight
B	No	No	F, B	Loose	Taught	Taught
C	Yes	Yes	F, B	Tight	Tight	Tight
D	Yes	No	F, B	Loose	Loose	Loose
E	Yes	No	F, B	Loose	Loose	Loose
F	Yes	No	F, B	Loose	Loose	Loose
G	No	Yes	F, B	Taught	Taught	Taught
H	Yes	No	No	Tight	Tight	Tight
I	No	No	F	Loose	Tight	Tight

A.



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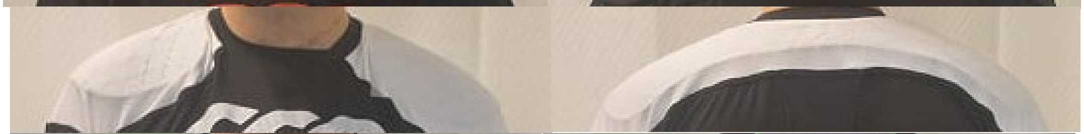

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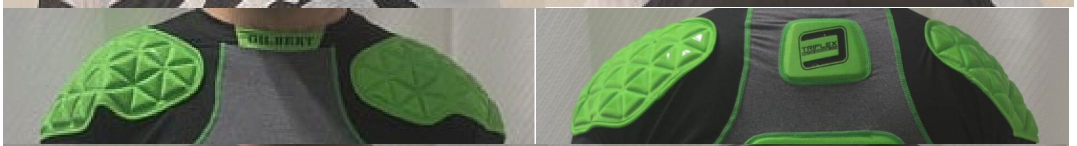

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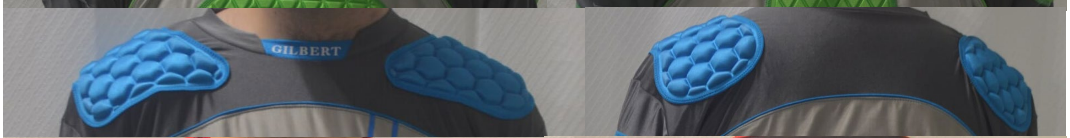

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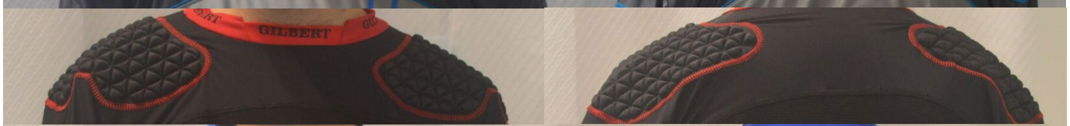

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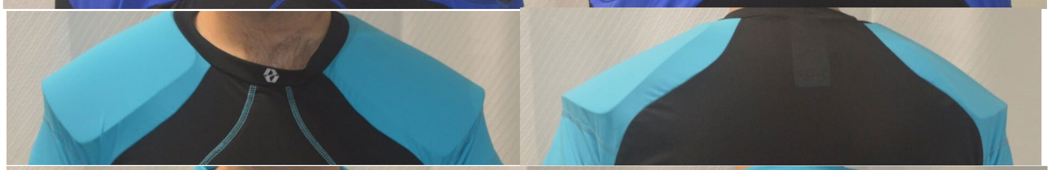

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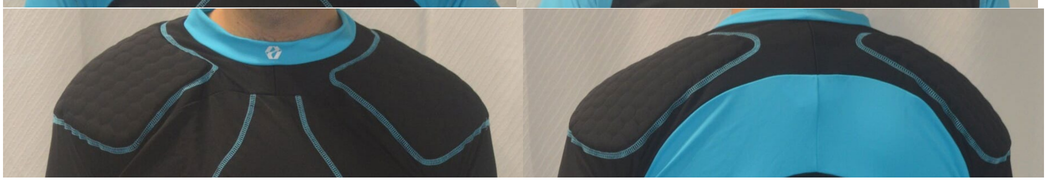

6. Participant 6

Picopress Measurement mmHg Tests 1, 2 and 3										
Garment and body position			Front				Back			
			1	2	3	Mean	1	2	3	Mean
	Canterbury Vapodri Raze	Position 1	0	2	0	0.7	2	1	2	1.7
		Position 2	0	0	0	0	1	1	1	1
		Position 3	0	0	0	0	0	0	0	0
		Position 4	2	2	2	2	0	0	0	0
	Canterbury Vapodri Raze pro	Position 1	2	4	2	2.7	2	1	2	1.7
		Position 2	0	0	0	0	4	3	4	3.7
		Position 3	0	0	0	0	1	1	1	1
		Position 4	0	1	0	0.3	0	0	0	0
	Gilbert Triflex Match V3	Position 1	7	2	2	3.7	3	1	3	2.3
		Position 2	0	0	0	0	1	2	2	1.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	1	1	0.7
	Gilbert Chieftain V3	Position 1	0	0	0	0	0	2	2	1.3
		Position 2	0	0	0	0	4	1	1	1.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Atomic Zenon	Position 1	6	8	6	6.7	1	1	1	1
		Position 2	1	0	0	0.3	0	1	1	0.7
		Position 3	0	1	0	0.3	1	0	1	0.7
		Position 4	0	0	0	0	0	0	0	0
	Gilbert Triflex XP1	Position 1	4	1	2	2.3	0	0	0	0
		Position 2	1	0	0	0.3	1	1	1	1
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	1	0	0.3	0	0	0	0
	Kooga IPS V	Position 1	1	0	0	0.3	5	1	3	3
		Position 2	0	0	0	0	3	2	3	2.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	0	0	0	0	0	0	0	0
	Body Armour Tech Vest BA	Position 1	0	0	0	0	5	3	5	4.3
		Position 2	0	0	0	0	4	3	4	3.7
		Position 3	0	0	0	0	0	0	0	0
		Position 4	1	1	1	1	0	0	0	0
	Body Armour Flexitop BA	Position 1	0	0	0	0	4	0	4	2.7
		Position 2	0	0	0	0	3	2	3	2.7
		Position 3	0	0	0	0	1	1	1	1
		Position 4	0	0	0	0	0	0	0	0

Appendix F.

Part 1:Tensile Displacement

Table 2: Lateral Expansion During Tensile Displacement

Shoulder Pads	Test	Tensile Displacement (cm/%)	Time (secs)	Biaxial Displacement			Difference Between Middle and Mean of T and B (%)
				Top (T)/ Bottom (B) (cm)	Mean Of T and B (cm/%)	Middle (M)(cm/%)	
C001	**1**	6.1/41	36	1.3/1.9	1.6/14	3.8/45	31
	2	6.2/41	37	1.5/2.5	2.0/17	4.0/47	30
	3	8.1/54	50	2.4/2.6	2.5/21	4.1/48	27
RS002	**1**	4.5/30	27	1.6/2.1	1.9/16	2.1/25	9
	2	5.1/34	30	1.9/2.4	2.2/19	2.1/25	6
	3	5.4/36	32	1.9/2.1	2.0/17	2.2/26	9
3PS003	**1**	5.4/36	40	0.6/1.4	1.0/9	2.4/28	19
	2	5.6/37	42	0.7/1.5	1.1/9	2.4/28	19
	3	6.2/ 41	46	0.8/1.6	1.2/10	2.6/31	21
4PS004	**1**	6.6/44	41	0.6/0.9	0.8/7	1.5/17	10
	2	8.0/53	49	1.1/1.0	1.1/10	1.8/20	10
	3	8.3/55	51	1.2/1.1	1.2/10	2.2/25	15
HC005	**1**	1.0/7	5	- 0.3 / - 0.3	- 0.3/- 3	- 0.2/- 2	1
	2	1.3/9	7	- 0.4 / - 0.3	- 0.4/- 3	- 0.7/- 8	-5
	3	1.3/9	7	- 0.4 / - 0.3	- 0.4/- 3	- 0.4/- 5	- 2

*measured to an assumed accuracy of 1 mm

Appendix G

Part 2: Tensile Displacement

Table 7: Lateral Expansion During Tensile Displacement

Shoulder Pads	Test	Tensile Displacement (cm/%)	Time (secs)	Biaxial Displacement			Difference Between Middle and Mean of T and B (%)
				Top (T)/ Bottom (B) (cm)	Mean Of T and B (cm/%)	Middle (M)(cm/%)	
RS006	**1**	2.2/15	17	0.5/0.5	0.5/4	1.5/18	14
	2	6.5/43	49	1.9/1.8	1.9/16	1.9/22	6
	3	6.8/45	51	2.0/1.9	2.0/16	2.0/24	8
RS007	**1**	3.6/24	22	0.4/0.9	0.7/6	2.0/24	18
	2	3.9/26	24	0.5/1.0	0.8/7	2.0/24	17
	3	4.6/31	29	0.6/1.2	0.9/8	2.0/24	16
RS008	**1**	3.6/24	22	0.6/0.6	0.6/5	2.0/24	19
	2	4.4/29	27	0.7/0.8	0.8/7	0.9/12	5
	3	5.5/37	34	0.7/1.1	0.9/8	1.9/22	14
RS009	**1**	1.9/13	12	0.0./0.2	0.1/1	1.0/12	11
	2	3.0/20	19	0.1/0.4	0.3/3	1.1/13	10
	3	4.7/31	29	0.2/0.4	0.3/3	1.2/14	11
RS010	**1**	3.7/25	18	0.3/0.2	0.3/3	2.9/34	31
	2	4.8/32	23	0.7/0.4	0.6/5	3.2/38	33
	3	5.5/37	27	1.3/0.5	0.9/8	3.2/38	30
RS011	**1**	3.2/21	19	0.8/0.9	0.9/8	2.5/29	21
	2	4.6/31	27	1.1/1.3	2.7/23	2.9/34	11
	3	6.4/43	38	1.4/1.5	1.5/12	2.7/32	20
RS012	**1**	3.7/25	21	1.1/0.9	1.0/9	2.9/34	25
	2	4.4/29	24	1.1/1.0	1.1/9	2.0/24	15
	3	4.6/31	26	1.2/1.0	1.1/9	3.0/35	26
RS013	**1**	4.0/27	24	0.6/0.2	0.4/3	1.8/21	18
	2	5.6/37	34	0.9/0.9	0.9/8	1.8/21	13
	3	6.5/43	39	0.9/1.0	1.0/11	1.7/15	4
RS014	**1**	6.4/43	39	0.5/0.7	0.6/5	0.8/9	4
	2	7.1/47	42	0.6/0.8	0.7/6	0.7/8	2
	3	8.9/59	53	0.7/0.8	0.8/6	0.6/7	1

*measured to an assumed accuracy of 1 mm