

IMPACT RESISTANT MATERIALS AND DESIGN PRINCIPLES FOR SPORTSWEAR

David Tyler[†] and Praburaj Venkatraman*

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Manchester Metropolitan University
Department of Clothing Design and Technology
Hollings Faculty, Old Hall Lane
Manchester, UK
M14 6HR
Email: d.tyler@mmu.ac.uk

[†] *Corresponding author* * *denotes speaker*

Abstract

Recently there had been a widespread use of high performance materials in sports wear with enhanced functionality. In sportswear, protection against impact is featured in products for skiwear, snowboarding, rugby, football, basketball, cycling, running shoes, and many others. There is a dearth of technical information about the range of materials being used and quantifiable measures of their effectiveness are rarely disseminated.

An experimental set up is discussed with the scope of obtaining reliable and valid data relating to materials and commercial products. Two experimental methods have been used to gain understanding of material properties: an impact attenuation test (which captures peak forces over time) and Tekscan® pressure sensors (which capture the areal dispersal of impact forces). Alongside these dynamic tests are measures of thickness, flexural rigidity and bulk density. It was found that thicker materials (10 mm) were effective in protecting against 5J impacts. However bulky inserts restricted free movement, which was a concern in designing garments. The outcomes from pressure sensors enabled to precisely measure and monitor profile of impact force applied on to the substrate.

Based on this work, three parameters identified which would determine the characteristics of materials, the energy absorption properties, the ability of materials to extend the duration of an impact and the ability of materials to broaden the area affected by an impact. Using the above parameters the research is able to design smart protective garments which will have materials to prevent impact injury by absorbing the impact, delaying the point impact force and distributing it across a wider area.

Key words: Impact resistant materials, Impact attenuation test, Pressure sensors, impact forces, flexural density and thickness.

Introduction

Impact injuries sustained by sports men and women is increasing due to competitive nature of the sport such as rugby, football, baseball, etc. and it affects their career. National Sports Medicine Institute, NSMI (www.nsmi.org.uk) stated that sports players experience injuries caused by impact or contact with objects, surfaces or other people. Injuries caused by impact and contact are common sports such as football and rugby and more dangerous sports such as motor racing, boxing and skiing. Often, contact with other people can cause an athlete to become off balance, or change direction quickly; this causes damage to the connective tissue and powerful direct contact may also cause a joint to become displaced. Impact injuries usually include spinal injuries, ligament and tendon damage, fractures and head and spinal injuries. Rugby for instance, has the highest risk per player per hour of all the major sports, of which 30% of injuries occur in shoulder after the knee (Funk, 2012). Marshall et al. (2002) reported that rugby is a high contact sport and players are likely to sustain a range of injuries. International Rugby Board regulations allow (IRB) players to wear shoulder pads, provided the pads are made of soft and thin material which may be incorporated in an under garment or jersey provided the pads cover the collarbone and shoulder. The padding material may not exceed 45 kg/m³ providing maximum coverage to shoulder region (IRB, 2012). In addition, the players may wear shin guards, ankle support, and head gear that conforms to IRB regulation 12.0 (IRB, 2012). Shoulder injuries result in sprains, strains, fractures, and dislocations (Brooks et al. 2005). Funk (2012) stated that 35% of all injuries in the shoulder region are recurrent ones and the player has a likelihood of sustaining an injury on the other shoulder.

A recent report stated that one in four rugby players will be injured during a season. Rugby injuries are three times higher than football. Most injuries are experienced by youth 10-18 years and adults aged 25-34 years of age. In rugby 57% of most sport injuries occur during matches than training and particularly when a player tackles or being tackled (South Wales Osteopathic Society, 2009). Concussion is an injury to brain or spinal cord due to jarring from a blow, fall or impact of a collision. In the Australian Football League, concussion is estimated to occur at a rate of approximately seven injuries per team per season (Khurana and Kaye, 2011). Rugby Football Union (RFU, 2002) stated that despite increase in use of shoulder pads from 20 to 36% between 1999 and 2002 there were increase in injuries from 12

to 13%. Gerrard (1998) noted that shoulder pads do not protect against fracture, dislocation or rotator cuff tears. It has been suggested shoulder pads may protect from lacerations, reduce bruising and haematoma of the soft tissue surrounding the shoulder and not to major injuries that is attributed to direct blow to the top of the shoulder or falling onto an out stretched hand. Recently, Harris and Spears (2008) conducted an investigation on four commercially shoulder pads – PVA foam (Kooga, Canterbury, Gilbert and Terminator) for their material properties by dropping hard and soft objects onto a force plate imparting peak impact forces at pre-determined height and measured their force-deformation data. Best performing pads was thickest; all pads were able to attenuate force for lower loads however at higher impact loads offered little protection. Pain et al. (2008) reported *in vivo* effectiveness of Kooga shoulder pads using Tekscan sensors that measured impact intensity on actual tackle on six male rugby players. The researchers reported that pads enabled to reduce peak forces up to 35% (impact with an object) and 40% for all tackles.

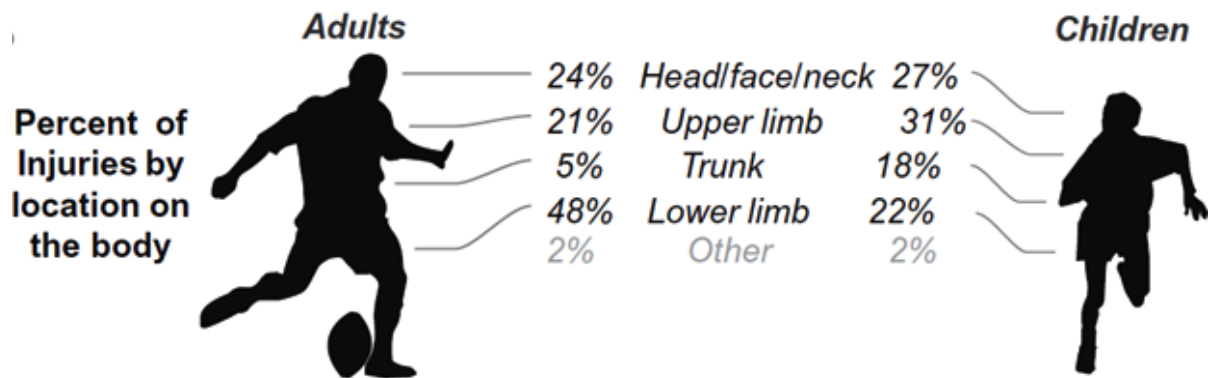


Figure 1: Proportion of injury sustained – adults/children

(Source: www.injuryresearch.bc.ca)

Figure 1 illustrates that adults endure more injury to head, shoulder and lower limb (thigh) whereas children suffer from head/neck injury followed by upper and lower limb.



Figure 2: Rugby player tackling

(Source: www.injuryresearch.bc.ca)

Approximately half of all injuries occur while a player is tackling (Figure 2) or being tackled. Hookers and flankers sustain the most injuries. Forwards are more frequently injured than backs because of their greater involvement in physical collisions and tackles (The British Columbia Injury Research and Prevention Unit, 2012). A rugby league team consists of 13 players (six forwards and seven backs); each team has sets of six tackles to advance the ball down field. Due to the nature of injuries sustained players may frequently lose opportunity from sports participation, hence teams are under pressure to prevent or reduce injuries to its players by wearing a protective gear. Figure 3 illustrates some of the injuries sustained by a rugby player with particular focus on tackler injuries.

This paper reflects on the recent exploration of impact resistance materials for sportswear using two experimental approaches to gain understanding of material properties using an impact attenuation test (which captures peak forces over time) and Tekscan® pressure sensors (which capture the areal dispersal of impact forces). Alongside these dynamic tests are measures of thickness, flexural rigidity and bulk density were gathered to ascertain their usefulness from a garment perspective. Finally, the paper focusses on presenting principles of designing sportswear using impact resistant materials.

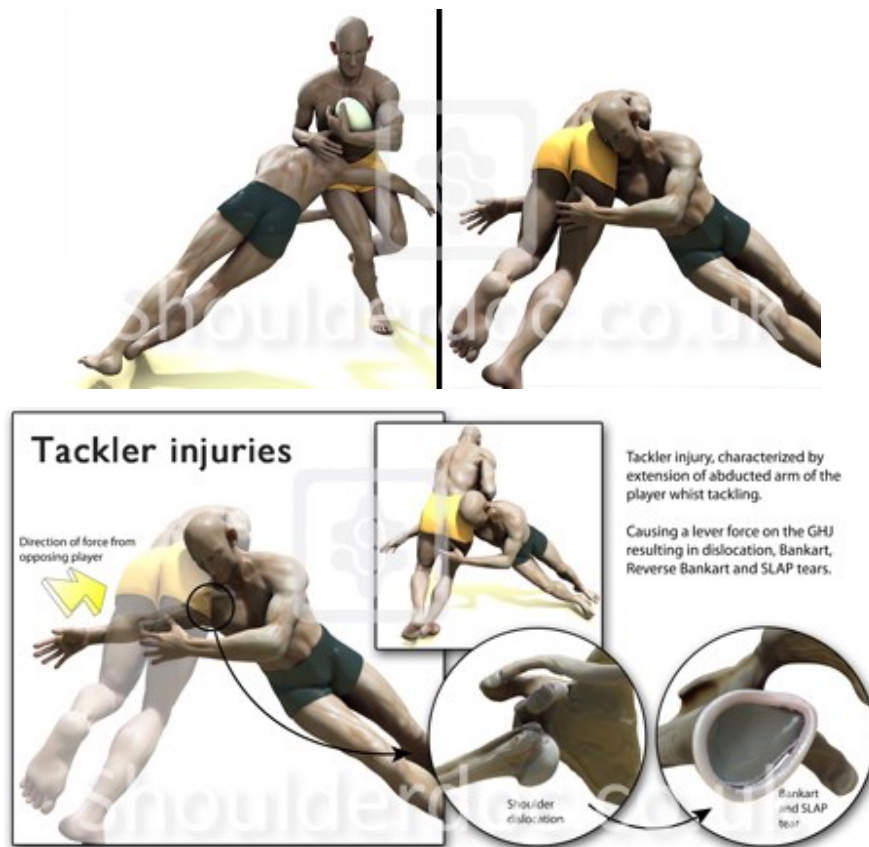


Figure 3 Rugby player injuries

Materials

A random selection of materials had been presented that are used in rugby vests for shoulder protection (Table 1 and 2).

Table 1 Currently available impact resistant materials

Commercial materials	Notes
1. D3O	Dilatant material
2. Poron XRD	Open cell urethane foam
3. EVA Foam	Ethyl vinyl acetate foam
4. Deflexion S-range Deflexion TP -range	3-dimensional spacer fabric with silicone Dilatant material
5. Spacer fabrics	3D knitted structure
6. Sorbothane	A synthetic visco elastic polymer
7. Leather	Natural benchmarking material

GPhlex is a similar material but not yet in widespread commercial use. The EVA foam was derived from a Canterbury rugby shirt, and the leather was a sample of unfinished material obtained from cow skin.

Poron XRD is open cell urethane foam. When at rest above the glass transition temperature of the urethane molecules, it has softness and flexibility. When impacted quickly, the glass transition temperature of the material drops so that the urethane molecules stiffen to protect the wearer from damage.

D3O is comprised of a polymer composite which contains a chemically engineered dilatant, an energy absorber. This basic material has been adapted and enhanced to meet specific performance standards and applications. The material is soft and flexible in its normal state, however when impacted by force it locks itself and disperses energy and returns to its normal state.

Ethylene vinyl acetate (EVA) foams are described as a specific type of cross-linked closed cell polyethylene foam. They are designed to be soft, with a rubber-like texture and with good shape recovery after deformation.

Deflexion was created by Dow Corning made of silicon that has been polymerized into a flexible silicone sheets. During a hard impact it like a bullet, all the molecules gather around that area and instant turn rock solid. They would disperse and absorb the impact, like a bullet-proof vest. The idea is to create a kind of armour that can shift around like clothing in a breathable fashion (Dow Corning, 2012).

Spacer fabric - A three-dimensional knitted structure that allows cushioning and shock absorbency with excellent recovery properties. Spacer fabrics are complex 3D constructions made of two separate fabric layers connected vertically with pile yarns or fabric layers. The conventional spacer fabrics composed of two surface layers bound with pile yarns are generally manufactured using weaving and knitting technologies (Abounaim et al, 2010).

Sorbothane – a synthetic visco elastic polymer (thermoset polyurethane material) used to absorb shock widely used in shoe insoles. It also possesses shock absorption, vibration insulation, and damping characteristics (www.sorbothane.com). Cinats et al. (1987) studied therapeutic implication of sorbothane in orthotic insoles which could absorb the energy from foot strike had some clinical significance, however properties of material may change when bonded to other substances in production of insoles for shoes.

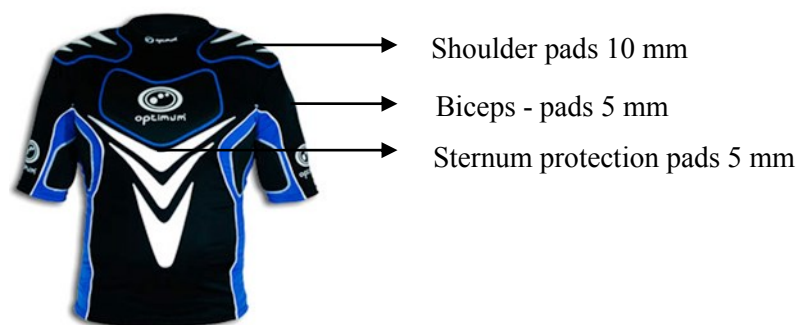


Figure 4 A typical Rugby shirt (Optimum) with impact resistant material insertion

Table 2 Leading brands providing shoulder pads for Rugby

Brand	Product	Impact resistant materials
Canterbury	 A black long-sleeved rugby jersey with red accents on the sleeves. It features a white Canterbury logo on the chest and a small 'Canterbury Flextop Plus' tag at the collar.	Honeycomb 5 mm foam padding on biceps, sternum and kidney areas.
Gilbert –Virtuo 12	 A black and blue long-sleeved rugby jersey. It features extensive blue padding on the shoulders, biceps, and chest. The Gilbert logo is visible on the chest.	Flexible 10 mm cellular foam on the shoulders allows for freedom of movement, maximum ventilation and padding in the key contact areas. The 12 strategically positioned pads, on the shoulders, biceps, sternum, kidneys and back provides all over protection
Optimum	 A black long-sleeved rugby jersey with blue and white accents. It features blue padding on the shoulders and chest. The Optimum logo is visible on the chest.	10 mm Shoulder pads, 5 mm pads for biceps and sternum.
Kooga- EVX V	 A black long-sleeved rugby jersey with yellow accents. It features yellow padding on the shoulders and biceps. The Kooga logo and 'EVX V' are visible on the chest.	EVX protection offers the optimum in fit and freedom of movement. The pads consist of a lycra body, shoulder, sternum, bicep padding, all comprised of high expanded EVA.

McDavid		Patented, lightweight, breathable, HexPad® athletic foam conforms to and stretches with body for continuous protection.
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There has been a considerable amount of literature (Laing and Carr, 2005) on sportswear products discussing on performance such as comfort, durability, functionality, etc. However there is a shortage of information relating to materials which are used for preventing from injuries sustained in sport related activities. This includes the level of impact or force sustained at the point of contact, capabilities of absorbing the shock without causing injury to the wearer, practicality of use in sportswear apparel and clothing.

In addition to the above, a range of composite materials were also explored such as coir/EVA as nonwoven impact protectors (Maklewska et al., 2005), polypropylene and flax fibre laminate (de Velde et al., 1998), cellular textile materials (Tao and Yu, 2002) as sports protectors for helmets. In addition, 3D spacer fabrics were explored by Dow Corning on varying thicknesses and levels of protection (Dow Corning, 2011). Researchers (Maklewska et al., 2002) compared the impact strength of nonwoven fabric pads intended for applications in protective clothing and sportswear. A Schob pendulum elastometer measured fabric resilience. An Instron tensile testing machine determined changes in deformation in relation to load. The 40 millimetre thick single layer, three-dimensional fabric exhibited a high relative absorption rate and low impact force, but was too thick for use in protective pads. The 20-millimetre thick multilayer fabric was more suitable. Researchers added that future research would address the manufacture of multilayer protective pads with a variety of fabrics having different properties.

Cushioning technology provider Roger Co. have reported two customisable products using its Poron XRD material (WSA, 2011), two versions were highlighted extreme impact pad and B-guard. The X-pad was recommended for knee and elbow pads to shin and thigh protection. The product has fabric backing that allows moisture wicking air channels to enhance comfort. Dura et al. (2002) investigated the behaviour of dynamic rigidity on shock absorbing

materials (used for shoes) using a visco-elastic linear model. This method was suitable for materials that repeatedly endure impact such as an athlete running on a track wearing a shoe (insoles).

Lam et al. (2004) studied various thermoplastic cellular textile composites with knitted and nonwoven fabrics which were sandwiched between layers of thermoplastic matrix (polypropylene or Low density polyethylene). Researchers reported the effect of impact energy of interlock knitted fabric in a matrix - ultra high molecular weight polyethylene/low density polyethylene on three levels of impact 24 J, 44 J and 119 J. The fabrics were in the form of domed-grids (cellular composites) with dome rising up to 15mm thickness. The fabrics did not collapse at low impact (24J) while at higher loads fabric deformed and cells closed at high impact energy. Cellular composites also had little recovery soon after impact.

Methodology

In order to ascertain material properties of impact resistant materials a range of methods were consulted and of the many two methods were suitable. Industrial bump caps (BS EN 812:1997/A1:2001) and specification for head protectors for cricketers (BS 7928:1998) involved a striker falling on a surface, with the protective product experiencing the impacts. The current research focuses on material properties, and measurements of deceleration are of less interest. Consequently, our experimental equipment detects the forces experienced by a transducer attached to an anvil located under the protective material. This method is in line with the IRB prescribed hammer and anvil test, which involves a flat striking surface (5 ± 0.02 kg) falling on to a “pad” resting on a steel anvil (Pain et al. 2008).

Impact attenuation test

The impact attenuation test has a striker, a steel ball, falling on to a flat anvil on which the protective material is placed. The pressure sensors are located below the sample material and the forces transmitted through the material by the impactor are recorded in the form of a load-vs-time data set. By varying the diameter of the ball, different impact profiles can be created. The mass/height of fall parameters determines the impact energy. For research purposes, impacts of 5J, 10J and 15J are used. An illustration of the test equipment is in Figure 5.

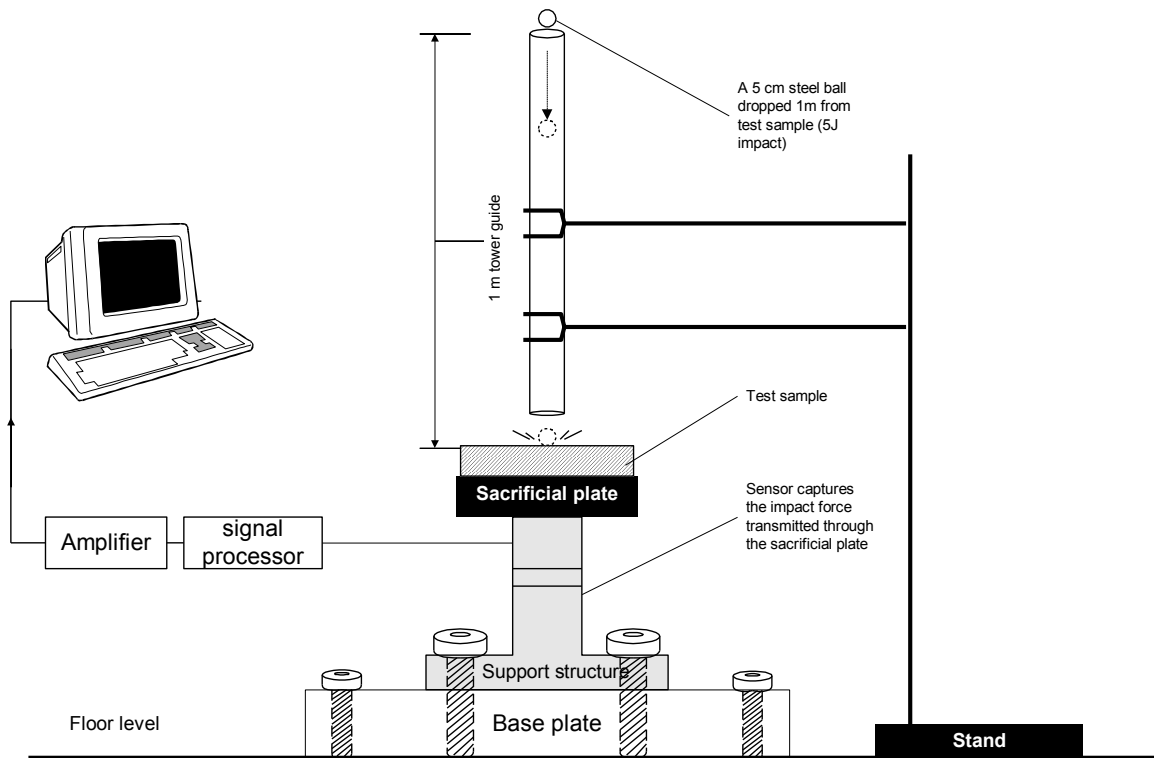


Figure 5 Impact attenuation test

The impact test made use of custom-built equipment from a testing company INSPEC, UK. A typical set of results recorded for a thin (3 mm) material is illustrated in Figure 6. There was insufficient energy taken out by the material, so the ball made a few bounces before coming to rest, and these movements are apparent in the test data.

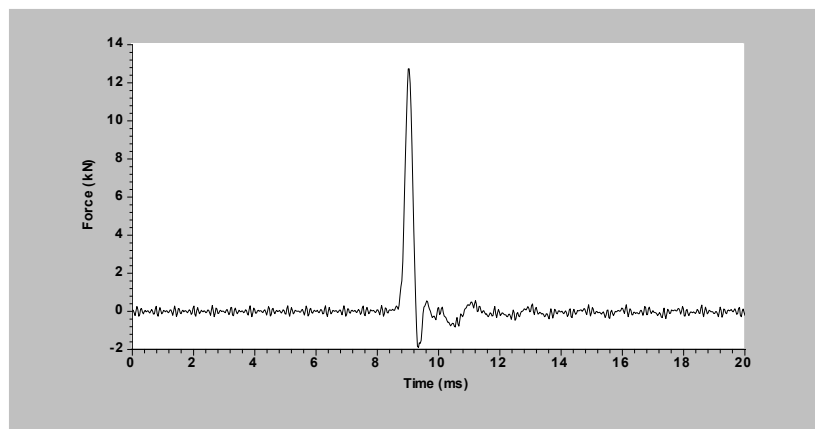


Figure 6 Impact forces experienced under a 3mm layer of Poron XRD (Peak force = 12.7 kN).

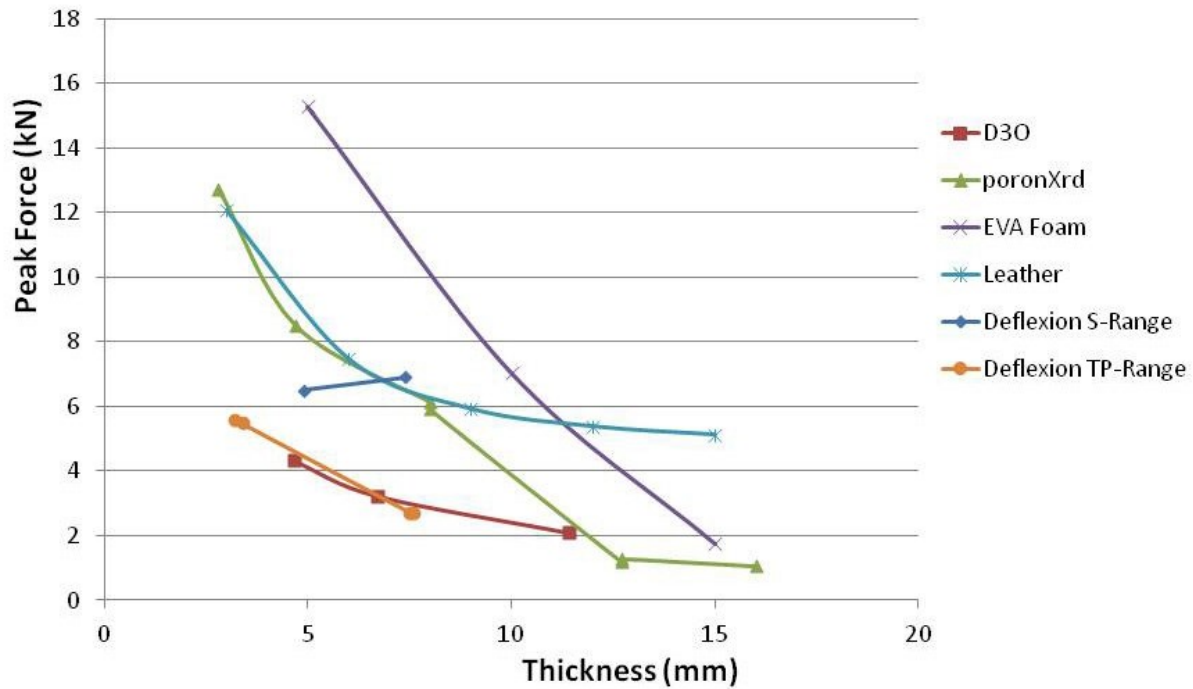


Figure 7 Measurement of peak force against varying material thickness

A selection of materials was tested to compare their abilities to protect against impact. As a control, unfinished leather was tested so that the commercial products could be benchmarked. Leather is a natural material that has been used to provide wearers with some protection. Figure 7 presents peak force variations for a range of materials with different thicknesses. Materials of 2-3 mm experienced high peak forces. As thicknesses increase, the commercial products designed to absorb energy and protect against impacts reduce peak forces more effectively than the leather sample.

The EVA foam samples were taken from commercial garments designed for rugby players. Neither the 5 mm (used for arm protection) nor the 10 mm (used for shoulder protection) compared favourably with leather. 10 mm is the maximum thickness permitted by the International Rugby Board for shoulder protection.

In general, the branded commercial materials performed better than leather, although less so below 5mm.

Of particular interest is the time of duration of the impacts. These vary significantly with thickness of the material being tested. Results for one impact-absorbing material are presented in Figure 8.

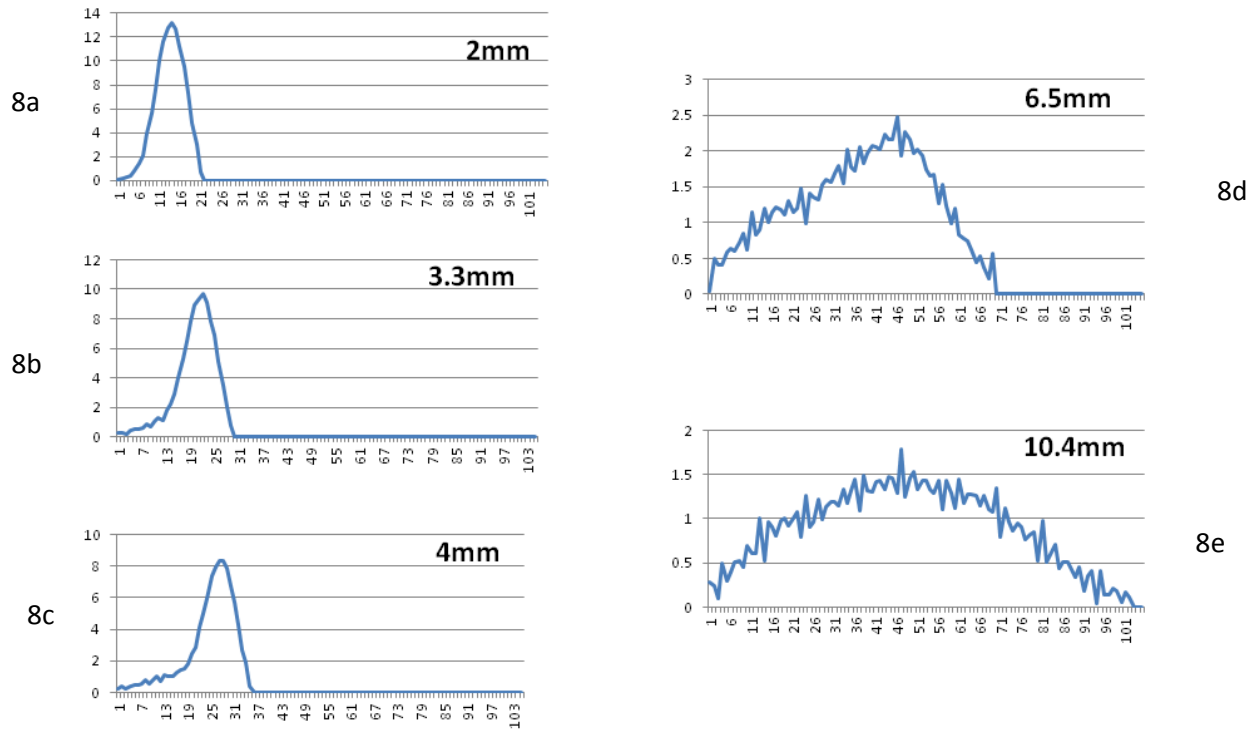


Figure 8: Test results to show the broadening of the impact forces resulting from the increasing thickness of the protective material

It can be noticed from Figure 8 that the peak forces transmitted through the material reduce as the thickness increases from 2 mm to 10.4 mm. This could be attributed to the fact that impact energy is dissipated and distributed within the material. The thicker material provides a cushioning effect such that the impact energy is absorbed and diminished by the material subsequently. In addition, the duration of impact was also recorded. As the thickness increased from 2 mm to 10.4 mm the duration of impact also increased from 21 milliseconds to 101 milliseconds, in other words, the material extended the time it took to reach its peak value. The results are significant because the thickness of material contributed to reduction of peak forces as well as extending the duration of impact. This is beneficial in the sense that the material will extend the duration of impact as well as reduce the impact force (absorbing energy) through the material. Earlier explorations (Venkatraman and Tyler 2011) revealed that the reduction in peak force with thickness was entirely predictable, as samples of 10mm thickness or more were effective in protecting against 5J impacts and the impacting sphere

produced no surface damage. However at 5 mm thickness the material experienced high impact forces. In the following experimental test the ability of the material to broaden the area of impact is presented using Tekscan findings.

Tekscan pressure sensors

The Tekscan pressure measurement system is an ultra-thin, tactile pressure sensor. Every Tekscan sensor is comprised of numerous individual sensing elements, or sensels. The sensel density represents the total number of sensels per unit of area. The system has mapping software which provides the output in the form of a colour coded pseudo-graph (Tekscan, 2011).

The pressure sensors are placed between the impactor and sample material and force transmitted on to the material are obtained in the form of data plots containing the colour-coded chart with red/orange colour indicating the highest pressure applied and blue areas indicating low pressure applied. Other researchers (Pain et al., 2008) have undertaken experiments using Tekscan where pressure sensors were placed in the vests and impact attenuation was measured.

Preliminary results have been obtained using a 75 mm steel ball impacting a 9 mm protective material. Figure 9 shows screen shots of a video recording from the Tekscan system. Frame 1 (Figure 9a) has the peak force showing mostly red areas signifying saturation of the sensels. Frame 10 (Figure 9b) has no red areas, signifying that the forces on individual sensels reduced very quickly. Furthermore, the area of contact reduces and all later frames record the weight of the ball distributed over a reduced area of contact. The resting profile of the ball is shown in Frame 168 (Figure 9c). The area of contact at frame 1 was approximately double the area of contact at rest.

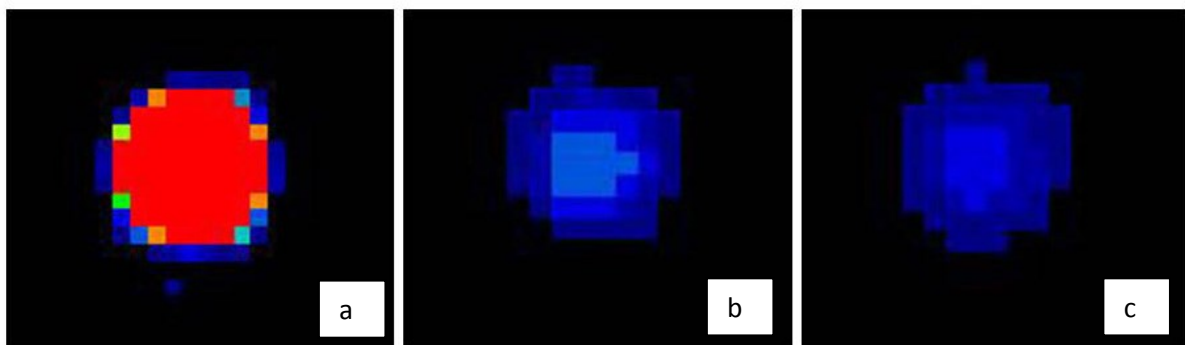


Figure 9: Tekscan screen shots (a: Frame 1, b: Frame 10, c: Frame 168) showing areas of contact and colour-coded impact forces.

Garment design using impact resistant materials

Sportswear products require various performance characteristics such as durability, comfort, identity and recognition, and functionality. However, these are dependent on the type of sport, level of physical activity, team or individual sport, intensity of sport, indoor or outdoor sport, frequency, age and other special functions (El Moghazy 2009). In the context of rugby with particular focus on protection from impact using pads or materials six factors were selected for discussion and these are: mechanism of injury, flexibility, bulkiness, breathability, thickness and ability to sew these pads on to the clothing. As discussed earlier bulky inserts are not well received by players as they restrict free movements as well as offer poor comfort. Designing functional protective gear for sports is challenging and demanding since protection is sometimes achieved at the expense of comfort (thick pads, stiff, heavy and multi-layered, non-breathable). Some of the factors that affect whilst designing and developing these garments are presented in Figure 10.

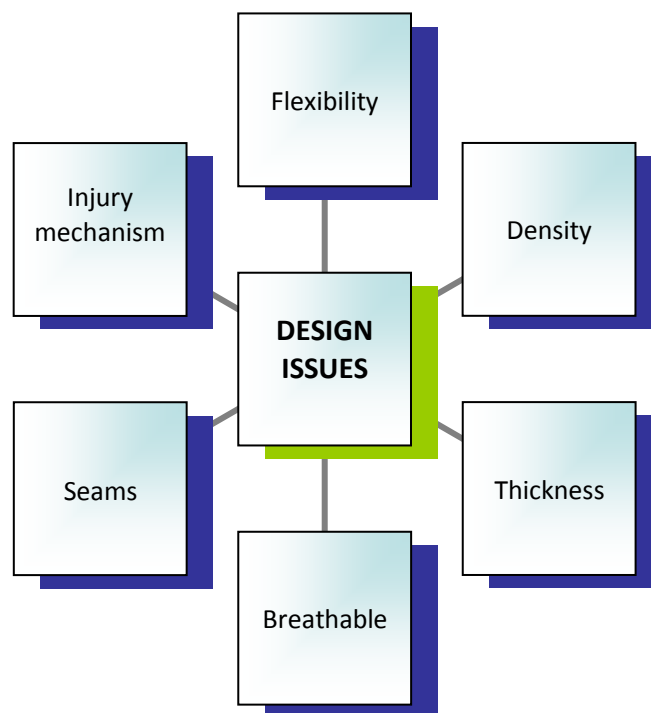


Figure 10 Factors influencing the design of garments with impact protection

Rugby is a high intensive team sport and players move fast in the field. Sport is popular among men; however women are getting more popularity particularly in college/school levels. As discussed earlier 40% of injuries are muscular strains or contusions, 30% are sprains, followed by dislocations, fractures, lacerations and overuse injuries. Players wear protective clothing in the form of head gear, padded vests, shorts, shin guards, mouth guards and support sleeves to reduce the risk of sprains and cramps. The International Rugby Board

had approved 59 brands that supply a wide range of shoulder padding vests to various teams (IRB, 2012). Having presented severity of injuries, popularity of sport, and demand for performance and material properties of a range of new material the final section outlines some of the concerns that affect the garment design and development utilising these protective materials.

Design issues

- Generally most of the pads or foams are available in thicknesses above 5 mm and it becomes a challenge to incorporate it in the garment.
- Pads for shoulders and sleeves lack any moulding of the shape. Pads used in some samples are large and garments do not fit well on the body when pads tend to hold the fabric out.
- Pads used in some products were smaller (shoulder region) which offered less protection to the wearer.
- Seams used in these garments were often over lock. Some products had body panels sewn together with flat lock seams which enhanced wearer comfort. Other products had pads that were sandwiched between fabrics in form of pouches.
- Thicker foams or pads have perforations to allow flexibility and moisture transport. However at other areas the pads block air/moisture movement allowing low breathability hence poor comfort.
- Pads were stiffer and allowed very little flexibility to conform to various contour of the shoulder region. Unlike heavy and bulky shoulder pads used for American Baseball the pads used for Rugby vests required flexibility



Figure 11 Typical Rugby vest with padding

(Source: www.kooga-rugby.com)

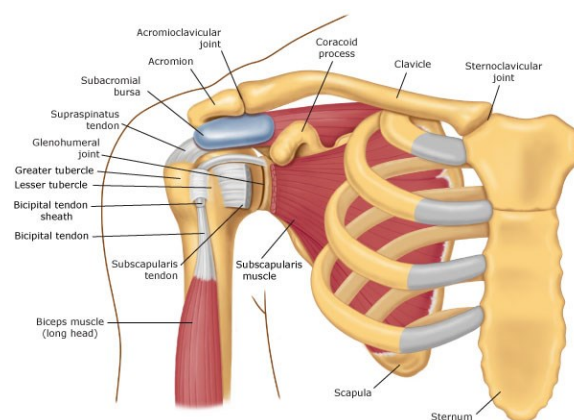


Figure 12 Shoulder Anatomy

(Source: <http://jimmysmithtraining.com>)

A recent epidemiological study by Crichton et al. (2011) investigated videos of 24 elite rugby players sustaining injury and reported that there were three common injury mechanisms in rugby resulting in serious shoulder injuries – ‘Try Scorer’, ‘Direct Impact’ and ‘Tackler’. It is necessary to understand the nature of the injury and design shoulder padding mechanisms which provide maximum protection to these common injury patterns.

1. Try scorer – out stretched arm when scoring a try
2. Direct impact - direct blow to the arm or shoulder when held by the side in neutral or slight adduction (moving of a body part toward the central axis of the body).
3. Tackler – it involves a levering force on the glenohumeral joint (GHJ) due to movement of the outstretched arm (Figure 12)

Knowledge of the mechanisms involved in rugby shoulder injury is useful in understanding the pathological injuries and aiding the development of injury prevention methods such as padded vests.

It could be noticed that a typical shoulder padded vest (Figure 11) do not provide complete coverage to the shoulder region in the context of the findings from Crichton et al. (2011). These design issues should be considered while producing garments for shoulder protection for Rugby. The shoulder pads should be flexible to cover the regions as shown in Figure 12 – they are sternoclavicular joint, acromioclavicular, and Glenohumeral joint. Clearly the padded vest as shown in Figure 11 did not provide protection to these regions satisfactorily. Pain et al. (2008) also reported that when tackled using a shoulder pad the reduction in force was noticed only in the acromioclavicular joint while forces in other areas of the shoulder region was not reduced. In other words, the shoulder experienced considerable impact during tackling. The paper emphasised the importance of six areas that affect the garment design; they are mechanism of injury, flexibility, bulkiness, breathability, thickness and ability to sew these pads on to the clothing. The research intends to explore material that is flexible, light weight, breathable, thin and allows easy movement of body. This is based on the principle that the material is able to extend the duration of an impact and the able to broaden the area affected by an impact such that the wearer do not experience peak forces during a fall or tackling.

Summary and Conclusions

This paper has highlighted the performance of protective materials used for rugby vests for prevention of shoulder injury. Rugby is a fast-paced contact sport that requires precise protection to the shoulder region particularly when players fall with out-stretched arms (when scoring a try) or tackling an opponent, or experiencing a direct impact onto the ground. Many studies have reported on the performance of protective materials and have been critically reviewed in this paper. This research is concerned with material properties and our experimental work has focused on the forces experienced by a transducer attached to an anvil under the protective material. Alongside this impact attenuation test, Tekscan equipment was utilised to advance understanding of the material properties. A random selection of Rugby vests was studied and the results are presented.

A selection of materials was tested to benchmark their capability to protect against impact. These were compared with unfinished leather: a material offering wearers some protection and used here as a control. Figure 7 presents peak force variations for a range of materials with different thicknesses. Materials of 2-3 mm experienced high peak forces. As thicknesses increase, the commercial products designed to absorb energy and protect against impacts reduce peak forces more effectively than the leather sample. A close examination of the sensor signals revealed that the duration of impact was extended and the forces experienced by the material were correspondingly reduced. Figure 8 documents the change for one particular sample from 21 ms to 101 ms as the thickness increases from 2 mm to 10.4 mm. The impact attenuation test records all the forces transmitted through the material and does not illuminate how those forces are distributed at the zone of impact. However, the Tekscan equipment has enabled the issue of areal distribution of forces to be analysed. Preliminary findings show that the area experiencing peak forces is approximately twice the area of contact between an object resting on a material. This provides an additional factor to understand the role of protective materials as they experience impacts.

Six factors affecting the design and development of performance sportswear are represented in Figure 10. We have analysed a selection of rugby shirts (with protective pads) using the six factors approach and have documented a number of issues for designers and product developers to consider. This analysis provides a framework for enhanced design and for the formulation of design principles for protective sportswear.

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