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The Application of Auxetic Material for Protective Sports Apparel †

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Abstract: Current research of auxetic materials highlights its potential as personal protective equipment for sports apparel with enhanced properties such as conformability, superior energy absorption and reduced thickness. In contrast, commercially available protective materials have proven to be problematic in that they inhibit movement, breathability, wicking and that molded pads are prone to saddling. Foam components are embedded within personal protective equipment for sports apparel, where protective material is positioned at regions of the body frequently exposed to injury of the soft tissue through collision, falls or hard impact. At present, the impact resistance of auxetic open cell polyurethane foam and some additively manufactured auxetic structures have been established, and processes for manufacturing curved auxetic materials as well as molding methods have been developed. Despite this, auxetic materials have not yet been applied as personal protective equipment for sports apparel in current research. This paper argues that there is scope to investigate auxetic materials potential for enhanced wearer functionality through properties of synclastic curvature and biaxial expansion.

Keywords: auxetic; PPE (personal protective equipment); sports apparel; polyurethane (PU) foam; synclastic curvature; conformability; garment technology; biaxial expansion

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1. Introduction

Auxetic materials have a negative Poisson's ratio (NPR), when subject to deformation they exhibit interesting characteristics, which have shown potential for protective sportswear. The materials laterally expand under stretch and laterally shrink under compression [1], and tailoring the value of negative Poisson's ratio enables a route to extreme values of properties including fracture toughness, synclastic curvature and indentation resistance [2]. At present, auxetic textiles exist as filaments, foams, yarns, fibres, fabrics and additively manufactured structures. Researchers suggest that auxetic materials, including NPR foam, could offer PPE for sports apparel improved conformability, superior energy absorption and reduced thickness/bulk [3]. The European Patent Office [4] includes patents in which these textiles are applied to sports technology, including 'Garments Having Auxetic Foam Layers'. Foam components are embedded within personal protective equipment (PPE) for sports apparel, where protective material is positioned at regions of the body frequently exposed to injury of the soft tissue through collision, fall or hard impact.

During sport, the body is exposed to the risks of the elements surrounding the player; PPE for sport is intended foremost to reduce the risk and severity of injury to the wearer without detracting from the nature of the sport [5]. Jakoet and Noakes [6] conducted a study on injury frequency sustained by the 416 rugby players from 16 countries participating in the 1995 Rugby World Cup concluding that injuries occurring from rugby are at the most frequent at the highest level of the game amongst the best players in the game. The overall injury frequency in the study was measured at 32 per 1,000 player hours and this increases to 43 per 1000 player hours during the final 7 matches, confirming a very high injury risk in Rugby Union, challenging views that superior fitness, skill and experience will lower risk of rugby injury. Padded clothing is an optional element of players dress in rugby and some individuals prefer to sacrifice protection simply because protective equipment is annoying [7], despite the high risk of the game, in that they inhibit movement, breathability, wicking, whilst molded pads are prone to saddling. Regulation 12 of the World Rugby regulations [8] relating to players dress does not stipulate a minimum area of protective shoulder coverage but does indicate the maximum such that across the depth of the Sternoclavicular (SC) joint is 60 mm, whilst the depth of the back of the neck is 70 mm and from the neck a maximum depth of 2 cm down the upper arm.

Auxetic polyurethane foams have been mechanically characterized for protective properties energy dissipation [9] and impact force attenuation [10] and a process for manufacturing curved auxetic foams have been developed [11]. Additionally, the synclastic curvature of auxetic foam has been demonstrated by placing auxetic and conventional foams over a domed surface to display the conformability of the auxetic material to the domed shape, in contrast to the conventional foam [12]. The current state of research relating to protective auxetic foams has a focus on optimizing fabrication methods [13] and the impact force attenuation [9] of auxetic materials. However, current research does not take a garment or fit approach and therefore neglects whether applying auxetic materials as PPE in combination with non-auxetic fabrics for apparel might hinder valuable auxetic sportswear properties, including enhanced conformability through synclastic curvature and biaxial expansion. This study compares auxetic foam, fabricated through an established method, against its conventional polyurethane (PU) counterpart as shoulder protective sports apparel. The study will focus on investigating the properties of enhanced synclastic curvature and conformability of auxetic foam versus its conventional counterpart, in combination with a sports top and a flexible joining technique; future work will investigate the impact and indentation resistant properties of auxetics in combination with garment technology.

2. Materials and Methods

This study investigates the effect of stretch and body curvatures on the dimensions of auxetic and conventional foam attached to the shoulder region of a sports top. The effect of stretch and body curvatures is quantified as the dimensional changes to the height, width and depth of the foams not under tension and when subject to tension by fitting the top to a mannequin. Conventional foam pads are known to restrict the stretch of sports tops, which can cause discomfort. In contrast, the structure of the auxetic foam unhinges and unfolds when subject to tension and therefore has potential to enable rather than restrict the stretch of the sports top. The study aims to take a garment approach to exploring the theory of enhanced conformability, in contrast to previous research of protective auxetics for sports applications [10], which has not developed garment applications.

2.1. Foam

Due to the pragmatic approach that this research takes, the study is limited to the use of small foam pads, although there is no minimum coverage for protective shoulder pads in the World Rugby regulations for players dress. At present, fabricating large-scale foams leads to surface creasing yet using through the thickness pins to reduce this effect marks permanent holes in the foam [12], in contrast the fabrication of small-scale foams enables a more consistent finish. Two conventional and two auxetic PU foams (Custom Foams, density 26–32 kg m^{-3}), measuring approximately 7 cm × 7 cm × 1 cm (height × width × depth), were used as shoulder padding for this study. The auxetic foams were converted using a thermo-mechanical method and triaxial compression. They were placed in an oven at 190 °C for 50 min, removed and gently stretched by hand in all three directions, then reinserted and placed in the oven for a further 10 min at 100 °C.

Each sample was subject to five impacts from a drop hammer with the energy of 2 J (1.608 kg from 0.13 m), when resting on a fixed flat surface. The drop hammer was fitted with an accelerometer that recorded acceleration at a rate of 50 kHz. In agreement with previous research peak forces for the auxetic foam were lower [10], ranging from 2090 N to 2488 N compared to 5579 N to 5965 N for the conventional foam.

2.2. Procedure

The men's mannequin selected was a size 40 (large) to accommodate for the top selected, also a large. Measurements were taken across various points and directions of the foam pads, including length, width and depth. Each measurement was taken with a tape measure and recorded to the nearest millimeter from three points, a centre point and either side, 2 cm from the edge to allow for varying points of tension on the foams and any inconsistencies in dimensions, as shown in Figure 1. Figure 1 shows the inside, middle and outside positions for each of the measurements: depth is shown on C2, width is indicated by C1 and length by A1. The tops were first measured on a flat surface (not subject to stretch) and then when fitted to a mannequin (subject to stretch); this procedure was repeated three times.

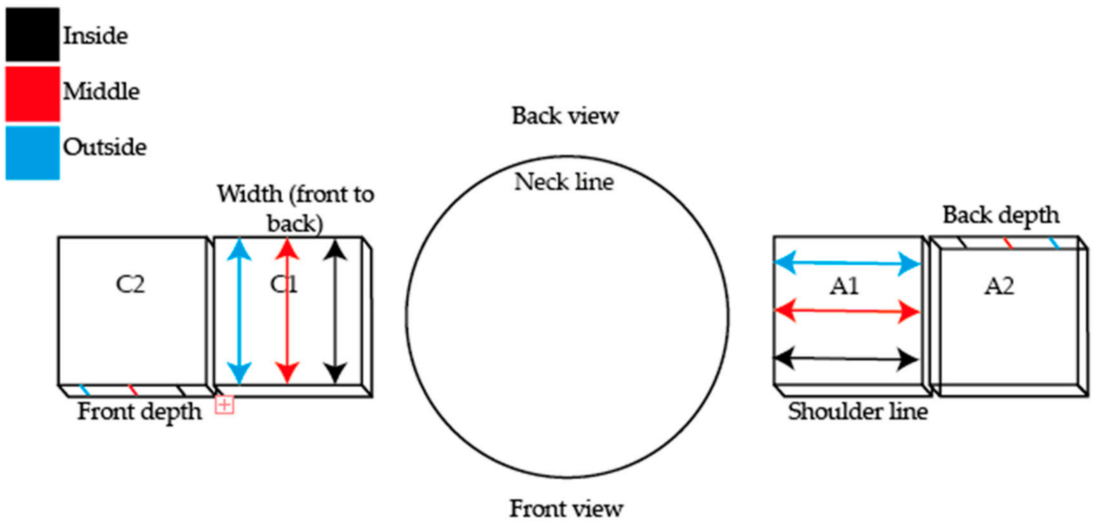

Figure 1. Diagram to display the shoulder padding positions of the conventional foams (C1 and C2) and auxetic foams (A1 and A2) and a key reference for the measurement positions of the front view depth, width, shoulder line and back view depth.

2.3. Construction Method

The construction method displayed in Table 1 shows that a bonding adhesive has been used to attach the foams to the tops rather than stitches; through using a method of construction that does not stitch down the edges of the foam nor embeds the pads, any change in the depth of the foams is clearly visible. The foams were positioned as shoulder protection on a pre made sports top, so that two auxetic foams (A1 and A2) are attached side-by-side to the left shoulder region and conventional (C1 and C2) for the opposite shoulder in order to show a comparison in material behavior, as shown in Figure 1. A men's raglan style nylon elastane sports top, size large, was selected for the study. The garment was placed on a mannequin and the shoulder protection region identified as the shoulder line of the mannequin, to begin 2 cm away from the neckline to give maximum coverage of the shoulder; this region was marked with tailor's chalk.

Table 1. Construction method.

No.	Machine	Operation
1	Iron	Lay the shiny side of the bonding film onto the back of all four foam samples heat seal tack with an iron.
2	Heat press	Secure the bonding film to the foam samples for 20 s at a temperature of 170 degrees.
3	Hand	Allow the samples to cool down and then peel back the plastic coating from the bonding film.
4	Iron	Heat seal tack the bonded side of the auxetic foams to the right side marked shoulder region, repeat on the left for the conventional foam.
5	Heat press	Secure the foam samples to the top for 20 s at a temperature of 170 degrees. Repeat for both sides.
6	-	Allow the bonding films to set for 24 h before trying on a mannequin.

3. Results

The quantified results from the three tests, presented in Table 2, indicate that the auxetic foam sample was able to retain its depth whilst subject to tension when fitted to a mannequin. In contrast the data shows that conventional foam was found to decrease in depth under tension and failed to recover its original depth from one test to the next. The results are also recorded as images in Figure 2 which offer a visual contrast between the conformability of the auxetic samples (images B and C) and the thinning conventional samples (images A and D). This conformability is highlighted through the front depth and back depth of the samples. The results confirm that the auxetic samples are able to offer enhanced conformability in combination with a stretch sports top than the conventional counterpart.

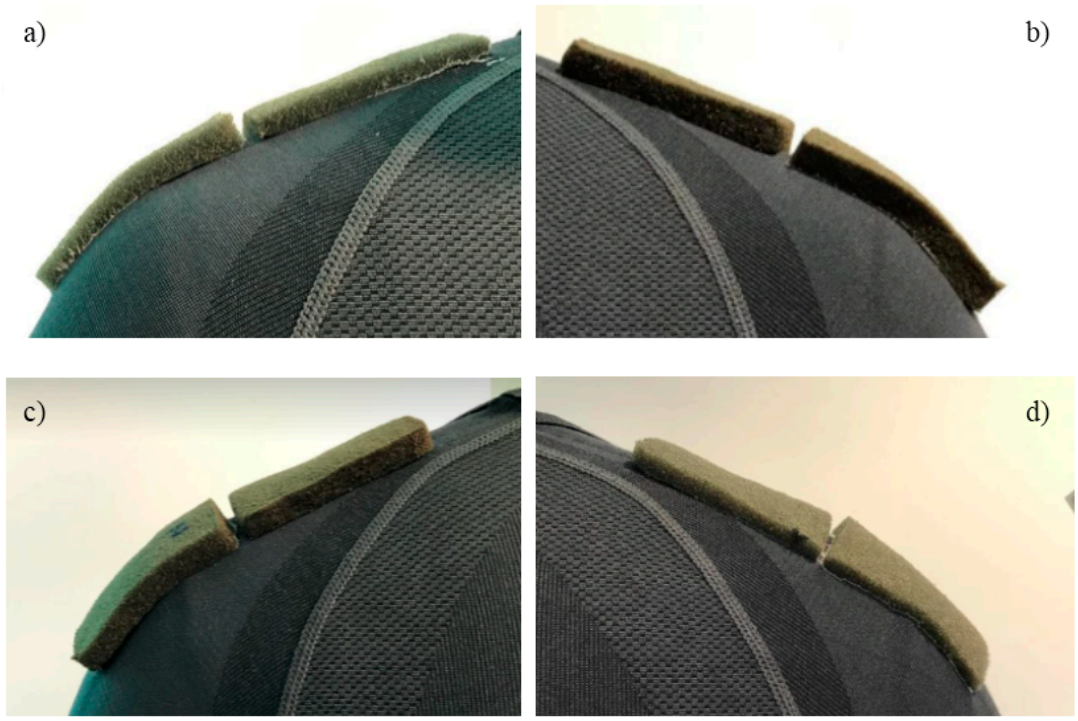

Figure 2. Images of the prototype garment, (**a**) front view conventional foam; (**b**) front view auxetic foam; (**c**) back view auxetic foam; (**d**) back view conventional foam.

Table 2. Measurements taken to the nearest millimetre of the depth (front and back), length and width of auxetic (A1 and A2) and conventional foam (C1 and C2) attached to a sports top, both on a flat surface (F) when subject to no tension and on a mannequin (M) and subject to tension.

	Front View Depth			Back View Depth			Length (Shoulder Line)			Width (Front to Back)		
	Outer	Middle	Inside	Outer	Middle	Inside	Outer	Middle	Inside	Outer	Middle	Inside
C1 FS	10, 9, 8	10, 8, 7	10, 8, 7	10, 8, 7	10, 8, 7	10, 8, 7	70, 70, 70	70, 70, 69	70, 69, 68	68, 69, 69	68, 69, 69	68, 68, 69
C1 M	9, 7, 7	8, 7, 7	7, 7, 6	7, 7, 7	7, 7, 7	8, 7, 7	66, 68, 67	66, 67, 67	66, 66, 66	72, 70, 70	72, 70, 70	72, 70, 70
C2 FS	10, 8, 7	10, 9, 8	10, 9, 9	10, 7, 7	10, 8, 8	10, 9, 8	70, 70, 69	70, 69, 68	70, 69, 67	68, 69, 70	68, 70, 70	68, 69, 70

C2 M	7, 7, 7	8, 8, 8	9, 9, 8	7, 6, 7	8, 7, 7	10, 8, 7	69, 68, 68	69, 67, 67	69, 67, 67	72, 72, 71	72, 72, 71	72, 72, 71
A1 FS	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	67, 67, 69	68, 68, 69	70, 69, 69	68, 68, 68	69, 69, 68	69, 69, 68
A1 M	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	68, 73, 72	69, 70, 71	71, 70, 70	74, 72, 76	74, 73, 76	74, 75, 75
A2 FS	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	71, 70, 70	71, 70, 70	71, 70, 70	70, 70, 69	68, 68, 68	68, 68, 68
A2 M	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	10, 10, 10	73, 74, 76	74, 76, 76	74, 76, 76	74, 75, 76	74, 76, 74	74, 75, 74

4. Discussion

The results reflect the hypothesis of researchers Liu and Hu [3] that NPR foam offers enhanced conformability as PPE attached to sports apparel. The difference in conformability of the two types of foams can be seen in Figure 2: images B and C show that the auxetic samples maintain an even depth when subject to tension from the stretched sports top, whereas images A and D show that under the same condition the conventional samples appear distorted and thinned across the depth. This is also evident in Table 2, the auxetic samples can be seen to maintain a depth of 10 mm between both the FS and M measurements whereas the conventional samples C1 and C2 decrease in depth between 1 and 3 mm from their original FS (flat surface) measurement when fitted to a mannequin (as shown by the M measurement). Through repeating the test three times, the results informed that the auxetic candidates (A1 and A2) exhibited excellent dimensional stability as the original depth is maintained through to the final test. In contrast, the conventional samples depleted in both front and back depth with each test, unable to recover the original depth.

The results regarding length and width also confirmed that the auxetic samples (A1 and A2) exhibited a higher level of conformability to sports apparel than the conventional samples (C1 and C2). Through biaxial expansion the auxetic samples extended across both width and length when fitted to a mannequin, where the largest increase is shown as 8 mm in width. In contrast, the conventional samples were able to extend in width by up to 4 mm, but they compensated for this extension through a reduction in length, which was also up to 4 mm. The pattern of increase in width implies that the PPE samples received the majority of tension from the stretch sports top across the width of the shoulder line. The results offer one avenue through which auxetic PPE offers enhanced conformability in combination with garment technology, through bonding; a wider set of results might have been gained from investigating different construction methods typically used to attach PPE to sports apparel, such as embedding and different stitches.

5. Conclusions

This was an exploratory study to demonstrate the material performance of auxetic versus conventional foam and investigate its functionality benefits as PPE for body wear. The prototype developed has built on current knowledge of auxetic materials by demonstrating the conformability of auxetic PU foams to the shoulder region through both biaxial expansion and synclastic curvature. The study does not focus on suitable garment technology or design and manufacture techniques, nor does it focus on developing auxetic fabrication methods. However, the results of the study do inform that auxetic foams are suitable candidates for further development as PPE in sports apparel and that future research should progress from this study by focusing on the optimum parameters for its application, including joining and embedding techniques as well as developing suitable complex auxetic shapes. Future research should also explore larger scale foams that have been designed to meet specified dimensions and a suitable curved shape.

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