THE POTENTIAL, THE PERFORMANCE AND THE BEHAVIOUR OF AUXETIC TEXTILE MATERIALS FOR COMPETITIVE AQUATIC SPORTS

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THE POTENTIAL, THE PERFORMANCE AND THE BEHAVIOUR OF AUXETIC TEXTILE MATERIALS FOR COMPETITIVE AQUATIC SPORTS

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I would like to thank my supervisory team for their guidance over the past year and to the technical team that have assisted me during my experimental work.

Dedication

I dedicate this thesis to my friends and family and to my parents in particular who have thoroughly supported me through my research.

Abstract

The project investigated how auxetic materials in the competitive aquatic sports (swimming wetsuits and impact protection vests) can support athletic performance. Auxetic materials are considered as a class of interesting and emerging materials with enhanced behaviour. Due to their negative Poisson's ratio, auxetic materials harbour unique characteristics such as, improved resistance to impact, synclastic curvature and viscoelastic dampening. Auxetic materials have been reported for a wide range of applications, including, functional performance sportswear, aerospace materials such as aeroplane nose cones, military textiles, medical equipment for example an antibiotic release bandage and geotextiles. However, there is little evidence of real time applications of auxetic materials and so this study investigated the application of auxetic materials for functional performance sportswear specifically competitive aquatic sports.

A critical appraisal of literature revealed the potential of materials to reduce hydrodynamic resistance during swimming and the performance of auxetic foams and textiles in water sports (vests) to provide impact resistance. In this study, a thermo-mechanical manufacturing technique was adopted on a reticulated Polyurethane foam to produce an auxetic foam with 70% linear compression ratio in three planes. Results revealed that the conversion process was in line with previous researches and conventional foam was successfully converted into auxetic foam. A uniaxial compression test found the auxetic foam cells to contract under compressive strain and resist compression at the same time. Initially indicating that the auxetic foams will be more resistant to impact.

The foams were subjected to an impact attenuation test developed by Department of Apparel, Manchester Metropolitan University. The results informed that auxetic foams can reduce peak impacts up 63% (3 times), which concurs with previous research. Auxetic foams therefore have the potential to provide enhanced resistance to impact in water sport protection vests. The auxetic foam was also evaluated for flexural rigidity and bending length. The converted auxetic foam achieved a 70% improvement in flexural rigidity measurement compared to conventional foams, indicating the auxetic foam has the potential to conform to body contours and therefore enhance the targeted compression in a competitive wetsuit. In addition, a commercially available competitive wetsuit was also examined for the potential of identifying where embedding of the auxetic materials in the garment would be most appropriate. The neoprene wetsuit evaluated in this project highlighted how functional materials are used within a conventional garment. Based on the above evaluation, it could be predicted that auxetic foams can be embedded into wetsuits for enhanced performance. Auxetic foams could enhance compression in highly compressive zones such as the buttocks, core and thighs without thinning out under tension, as conventional materials do. Their ability to contract under compression and extend under tension also suggests their suitability to shoulder and under arm panels where greater flexibility and freedom of movement is key. Auxetic therefore foams have the potential to reduce pressure and improve comfort in these areas. The above investigations reveal the potential of auxetic foams in competitive aquatic sports to reduce hydrodynamic resistance in a swimming wetsuit and offer enhanced impact resistance in a water sport protection vest.

Key Words: Auxetic, negative Poisson's ratio (NPR), auxetic foam, thermo-mechanical process, flexural rigidity, impact attenuation testing, compression, aquatic watersports application.

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List of Abbreviations

NPR Negative Poisson's ratio

MMU Manchester Metropolitan University

List of measured Abbreviations

g Grams

kg Kilograms

kN Kilonewtons

cm Centimetre

mm Millimetre

m Metre

µNm Micronewtonmetre

Chapter 1. Background & Introduction

Auxetic materials exhibit extremely unconventional mechanical characteristics and as a result, they are considered by key researchers to be a novel class of interesting, functional materials (Alderson and Alderson, 2007; Bhattacharya et al. 2014). When subjected to uniaxial tension in the longitudinal direction, conventional materials become longer in the extended direction and simultaneously contracted in the crosswise direction. Alternatively, when traditional materials are compressed, they tend to 'bulk'. Auxetic materials on the other hand are counter-intuitive, they expand when they are under uniaxial tension and laterally contract when compressed (Chan and Evans, 1998; Darja et al. 2013; Wang and Hu, 2014). The mechanism behind auxetic materials' exceptional elastic properties lies within the Poisson's ratio value of the material. When describing the elastic behaviour of a material, there are four constants of characterisation, these are; shear moduli (G), bulk moduli (K), Young's Moduli (E) and the Poisson's ratio (v). The Poisson's ratio is the ratio describing the contraction in the transverse direction to the longitudinal extension in the specified directions of stretching. Conventional materials exhibit a positive Poisson's ratio value, whereas auxetic materials are characterised by their negative Poisson's ratio or NPR (Yang et al. 2004). Alderson and Alderson, (2007) particularly describe them as an 'emerging class of materials', which draws attention to how they are becoming a prominent subject of research. Scientists and researchers have engaged with developing and exploring materials with negative Poisson's ratio in recent years for a wide range of potential applications in industries such as; personal protective clothing, geotextiles, filtration systems, aerospace, performance sportswear, automotive, medical textiles (Ugbolue et al. 2010; Alderson et al. 2012; Critchley et al. 2013a).

Man-made materials that possess a negative Poisson's ratio have been developed in all four areas of material classifications: metals, polymers, ceramics and composites (Yang et al. 2004). More recently, research and the development of negative Poisson's ratio materials has been an expanding area of interest gaining momentum in the technical textiles industry. This is evident in the growing amount of research dedicated to exploring auxetic textiles and their potential (Darja et al. 2013; Alderson et al. 2014). The recognised increase in the demand for the development of high performance and technically smart materials over the past thirty years is determined a direct result of the vast engineering and design improvements in industries such as aerospace, sports and automotive (Kulshreshtha and Vasile 2002; Alderson and Alderson, 2007). A growth in demand for highly functional and specialised application clothing has directly encouraged the active development of technical fibres, yarns and fabric structures (Gupta, 2011). For example, over the past two decades, functional sportswear, which can be characterised as garments worn during “maximum physical activity” or high impact sport such as swimming and athletics, has witnessed significant market growth (Manshahia and Dasa, 2014). Aside from physical factors such as training and body physique, athletes can look to their competitive sports garments to help them gain an advantage over their competitors (Nusser and Senner 2010). In racing sports where the difference in time between athletes can be measured as little as one hundredth of a second, much effort has been invested into developing textiles and materials that can improve an athlete’s performance through competitive advantage (Pendergast et al. 2006; Nusser and Senner 2010). As a result of this, sportswear brands and technical textile companies have invested in the development of functional fabrics and materials. A sport where the development of technical textiles and materials is notably evident is competitive swimming. Brands such as Speedo and Tyr have utilised novel technology and pioneering materials in their competitive swimsuits to further improve athlete swimming performances (Wu, 2011).

Auxetic materials and textiles have been highlighted by subject researchers for their potential applications in sports equipment and garments (Alderson et al. 2012; Sanami et al. 2014; Allen et al. 2015a). This study acts upon these recommendations and investigates the potential, performance and behaviour of auxetic materials for aquatic sports applications, in particular competitive swimming and water sport impact protection vests for sports such as kitesurfing and windsurfing. Many conceivable applications of auxetic materials have been discussed throughout literature, though much of the research contribution in this area is specific to the development of original negative Poisson’s ratio materials and not necessarily to the characterisation of their real-time use. Evidently, real-time employment of auxetic materials is still at preliminary development stages as it is assumed that their use in real applications is very limited. Academic literature suggests that the future of research in this area should have a focus of actual application, particularly within the performance textile industry (Wang and

Hu, 2014). This study analyses the factors that influence athletes in competitive aquatic sports and identifies where auxetic technology has the potential to benefit athletes. Utilising the process of development, auxetic foams were manufactured and examined for their potential application in competitive swimming and water sport protection vests.

This study employed manual test methods of examining the auxetic foams produced and it is acknowledged that there are other, quicker methods that can be applied. For example, quasi-static compression testing is desirable to ascertain the Poisson's ratio of converted foam, whereas this study used a compression method that required the researcher to take manual measurements and calculate the Poisson's ratio from the results, rather than this being achieved through computer software. However, these methods are still valid and produced reliable results and they were therefore utilised due to the limited access to other equipment.

1. 1. Research Aims

Aim 1: To critically appraise auxetic textile materials (foams and textiles) for their potential, performance and behaviour for competitive aquatic sport applications.

Aim 2: To analyse contextual factors that influence the performance of athletes in competitive aquatic sports.

Aim 3: To develop auxetic foams and assess their suitability, behaviour and potential in competitive swimming wetsuits and water sport impact protection vests.

Chapter 2. Literature Review

Competitive aquatic sports, specifically competitive swimming and watersports, require garments to be made from functional materials in order to help improve their racing time or protect them from potential dangers in high-risk sporting situations. The literature review investigates fabrication processes of auxetic materials and auxetic material behaviours in order to examine how auxetic foams have the potential to enhance these water sport situations. Although research papers developing and examining auxetic foams for sporting applications are limited, it is a growing area of study. However, no studies were found at the time of conducting this research interested in researching auxetic foams specifically for water sport applications, most of the studies are focused on impact resistance, this research therefore intends to investigate this gap in literature and offer a preliminary study.

2. 1. Auxetic Materials and Their Potential to Enhance Competitive Aquatic Sports

This section of the literature review will address the first objective: To critically appraise auxetic textile materials for their potential, performance and behaviour for competitive aquatic sportswear applications. At this point, the research continues down two distinct avenues, the first is to consider how auxetic foam may enhance resistance features in protective vests used in watersports such as kitesurfing and windsurfing. The second is to predict the potential of auxetic materials to enhance competitive swimming performance.

2.1.1. What are Auxetic Materials?

It has been recognised for more than a century that materials with auxetic properties exist within nature, for example in many biological materials; these include but are not limited to, animal skin including cat skin and the skin of cow teats and cancellous bone found in humans (Alderson & Alderson 2007; Critchley et al. 2013b; Wang and Hu, 2014). Since the discovery of auxetic materials in nature, the auxetic effect of materials has been continuously investigated and developed into many man-made forms in order to benefit a wide range of potential applications and industries. Materials that exhibit a negative Poisson's ratio are considered to harbour enhanced properties. Some of the main benefits of these materials include; increased resilience to strain and indentation, improved shear resistance, fracture toughness, out of plane stiffness and increased strength in curved shapes (synclastic curvature), sound absorption and vibration dampening (Chan and Evans, 1998; Scarpa 2002; Yang et al. 2004; Critchley et al. 2013b; Alderson and Alderson, 2007). Their unique set of characteristics suggests that they can be very attractive to certain industries, these include but are not limited to; high performance sportswear and apparatus, medical industries, personal protection, control underwear, automotive textiles, military textiles and aerospace textiles (Alderson and Alderson, 2007; Darja et al. 2013). The first manufactured material to exhibit a negative Poisson's ratio was a polyurethane foam that possessed a re-entrant structure, produced by Lakes (1987). Another auxetic material research pioneer, Ken Evans, later suggested the term 'auxetic' in 1991 to group the research performed in this area and so it has been conducted and produced under this terminology ever since (Wang and Hu, 2014).

In general, all materials are classed as one of two categories, either functional or structural in relation to their properties. The unique characteristics of auxetic materials determines that they harbour a combination of both characteristics and therefore are uniquely considered as structural and functional materials. Structural materials are defined by their mechanical physical properties by which they are designed to bear load or stress and functional materials on the other hand are classified by their ability to react or change in response to stimuli. For example, auxetic materials have the unique ability to provide improved impact resistance and also lateral expansion in response to lengthwise extension (Alderson 1999; Hu et al. 2011).

2.1.2. Auxetic Fibres

Currently, there are two ways to produce auxetic textiles; the first develops a fibre which itself displays a negative Poisson's ratio. The second develops an auxetic structure from conventional materials. Within the second option, there are two routes to creating structural auxetic textiles, these include; developing an auxetic yarn devised from conventional fibres and it also involves the creation of auxetic fabric structures (knitted and woven) where the fibre and yarn itself is again conventional (Darja et al. 2013).

The first auxetic fibre was developed in 2001 and since then, fabrication processes to produce Polypropylene, Polyester and Polyamide auxetic fibres have been established (Alderson and Alderson, 2007). Sloan et al. (2011) suggest, in theory, that auxetic fibres can be integrated during the manufacturing process into technical textiles to create enhanced performance and a blend of unique fabric properties, though this does not appear to have been achieved yet. Auxetic research experts at the University of Bolton have previously claimed to have developed prototype textiles with the auxetic fibres, yet no publications were found at the time of conducting this research (Darja et al. 2013).

Many of the papers dedicated to researching and developing auxetic textiles focus on the manufacture of structural auxetic textiles and yarns and therefore true auxetic fibres are not discussed in depth in this project. As the production of auxetic fabrics from auxetic fibres remains in the premature stages of development, they are not researched further in the context of this project.

2.1.3. Structural Auxetic Materials

Structural auxetic materials in the context of this research are defined as conventional materials with a positive Poisson's ratio that have been manufactured using new or existing techniques to create an auxetic structure that allows a negative Poisson's ratio to be present. For example, conventional polymeric yarns with inherent positive Poisson's ratio can be arranged into a particular auxetic geometric formation, which facilitates the resulting material to be auxetic and exhibit a negative Poisson's ratio. Such materials can be produced using conventional (knitting and weaving) manufacturing techniques. For the purpose of this research, auxetic foams are classed into the group of 'auxetic structures' as auxetic foam is made from conventional polymers and the unconventional structure causes the foam to have a negative Poisson's ratio. Auxetic textile structures and auxetic yarns are also classed as structural auxetic materials, as again they are produced from conventional fibres and it is their structure geometry that creates the auxetic behaviour.

2. 2. Cellular Solid Auxetic Materials

The development of auxetic cellular solids has predominantly focused on two classes of manufactured polymeric materials, which are, foams and honeycombs. Auxetic cellular solids have been recommended by researchers as suitable in sports applications (Sanami et al. 2014).

2.2.1. Auxetic Honeycombs

Honeycombs by nature are not considered suitable for aquatic sports applications within this project and are therefore not researched any further. However, it is important to acknowledge that they are researched by academics for use within sports equipment. Sanami et al. (2014) have developed a Finite Element Analysis simulation of a chiral arrowhead geometry auxetic honeycomb with the potential for use within sports applications, including protective equipment such as cycling helmets.

2.2.2. Auxetic Foams

Auxetic polymeric and metallic foams have been researched and manufactured since they were first developed in the late 1970's by Lakes and his researchers. The auxetic behaviour in polymeric foams occurs in the microstructure of the foam, in other words the ability for a foam to be auxetic is directly related to the shape of the foam cells. Traditional foams have a conventional, convex cell structure, auxetic foams on the other hand have 'concave' cell shape or a 're-entrant' structure (Alderson and Alderson, 2007; Grima et al. 2009). For the purposes of this study, only polymeric foams will be investigated and developed. It is also important to note at this point that there are a range of manufacturing techniques used to develop auxetic foams, such as the chemo-mechanical method and variations on the traditional thermo-mechanical method discussed below (Critchley et al. 2013a). For the purpose of this study, the traditional thermo-mechanical conversion process is investigated in great detail as it is utilised in the primary research methods.

2.2.3. Auxetic Foam Fabrication Processes

The thermo-mechanical process utilising open cell polyurethane foam is the most investigated method of fabricating conventional to auxetic foam conversion. This three stage method was originally developed by Lakes in 1987 and involved tri-axial volumetric compression, heating and a cooling stage. However common issues with the resultant converted foam produced by this process have been acknowledged by researchers. The most prevalent issue with the thermo-mechanical conversion process is the difficulty in producing fully homogenised samples. This is because it is challenging to position the conventional foam uniformly in the conversion mould and as a result, the individual foam cells may not converted in a fully repeatable standard (Critchley et al 2013b; Chan and Evans 1997a). Researchers have worked to improve the thermo-mechanical process to eliminate issues with converted foams and other studies conducted have investigated new and novel ways to convert auxetic foam.

2.2.4. 3D Printing Method

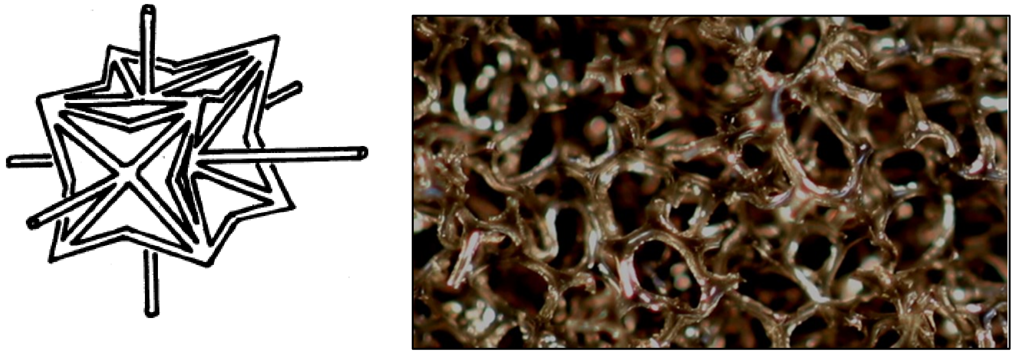
Critchley et al (2013b) successfully produced auxetic foam through a novel process of 3D printing foam in a re-entrant structure using pliable polymers. Ideally, 3D printing the re-entrant structure should eliminate the variability in individual foam shape and instead produce a fully repeatable cell structure. Which in theory, should eliminate issues when converting foam using the thermo-mechanical method. However, the researchers found the samples to vary widely in Poisson's ratio value. Two main reasons were attributed to the cause of the variance. Firstly, unavoidable systematic errors associated with the production process caused varying in internal cell angles and therefore all cell features were not uniformly the same, which affected the Poisson's ratio value for each individual cell. Secondly, removing the support material from the 3D printed foam through immersion into potassium hydroxide solution resulted in the cellular structure swelling, which applied stress to the structure and as a result individual cells were damaged (fractured, cracked or delaminated). Therefore when the samples were examined under strain, broken or damaged cells inevitably deformed through rotation and shear. Despite the standardisation issues that arised when 3D printing auxetic foam, although the study is considered as preliminary research, the results are a promising foundation for future development.

2.2.5. Chemo-Mechanical Method

Fabricating auxetic foams using a chemo-mechanical process has not yet been as widely explored as the traditional thermo-mechanical process (Grima et al. 2009; Gatt, 2011; Critchley et al. 2013a). Researchers, (Grima et al. 2009 and Gatt et al, 2011) explored a novel process which required the conventional foam to be compressed triaxially, as is followed in the traditional thermo-mechanical method, but instead of applying heat, the compressed foam was immersed into a solvent-based chemical and then air-dried in a compressed state. As a result an auxetic foam was successfully produced, the researchers also found that re-immersing the auxetic foam into the solvent can convert the NPR foam back to its conventional state. It can be suggested that this process may limit the end application of such foams but as the study is preliminary in nature, it also offers a base for future research to further explore other solvent and foam type combinations and eventually to tailor the process based on the end application of the resultant auxetic foam.

2.2.6. Thermo-Mechanical Fabrication Process

Lakes and his researchers were the first academics to develop a manufacturing process to convert a small sample (of dimensions 22mm x 22mm x 125mm) of conventional polymeric open-cell foam exhibiting a positive Poisson's ratio to an auxetic foam with a negative Poisson's ratio (NPR) in 1978. Since Lakes' development, the manufacturing process has been adapted and modified by other researchers. However, the main concepts of the Lakes' method (compression followed by heating and cooling) have largely remained the same. The method of thermo-mechanical conversion firstly requires the foam to be compressed tri-axially, usually in a metal mould, in order to buckle the cell ribs into a concave position; this creates the desired re-entrant structure. A drawing of the re-entrant cell structure by Lakes (1978) and an image of converted auxetic cells taken by Allen et al. (2015b) can be seen in figure 2.1. In order for the transformation in the cell ribs to hold, the specimen must be heated to just above its softening temperature. Cooling at room temperature allows the new foam structure to maintain potential energy; this is then followed by a relaxation phase. Heating temperature, time constraints and volumetric compression ratio are parameters that are fully dependent upon open or closed cell foam structure, along with the density of the solid (Lakes, 1978; Chan and Evans 1997; 1998: Yang et al. 2004: Critchley et al. 2013a). When considering the body of work in this area, Critchley et al. (2013a) have found that most researchers compressed the conventional foam to between 50% and 80% of its original size to yield the most successful conversion results.



(a) **(b)**

(a)Re-entrant cell structure drawing, Lakes (1987), (b) Converted auxetic foam cells, Allen et al. (2015b).

Figure 2.1 Re-entrant cell structures**.**

However, it was found that when using Lakes' original process, creasing upon the surface of the foam became a by-product of the single-stage compression process along with the potential for the auxetic foam to revert to its original specification, which is also described as creep (Chan and Evans 1997). In the late nineties, another auxetic foam research pioneer Ken Evans devised an improved auxetic foam fabrication process that was developed based upon Lakes' original triaxial-compression and heat combination method. In order to reduce surface creasing that is experienced when producing larger samples in particular (starting dimensions 300mm x 300mm x 100mm), the compression phase was split into four stages. Each stage exerted a small compression ratio over the foam, thus reducing its size incrementally towards the required dimensions. Increasing the temperature and length of the heating process was also required for the larger sample (Chan and Evans, 1997).

Other researchers (Duncan et al. 2016) have also concluded the influence of specimen shape to successful conversion of large samples. Cuboidal geometries of conventional foams were found to enable quicker and more even heat transfer during the conversion process in comparison to cuboid shapes and therefore more accurate and homogenous results. Foetal stage research by Duncan et al. (2016) involved the development of a conversion mould with through pins which successfully reduced surface deformation of large scale thin converted foams (150mm x 150mm x 30mm). The study concluded that having more control over conversion parameters enables future development to produce sport safety specific auxetic foams.

2.2.7. More Recent Studies Using the Multi-Stage Thermo-Mechanical Process

More recently, prominent researchers of this subject (Gatt et al. 2011; Sanami et al. 2014; Allen et al. 2015b) have successfully produced auxetic foams of smaller dimensions (original dimensions between 57mm^3 and 143mm^3) in comparison to the samples produced by Chan and Evans (1997), using a more simple thermo-mechanical multi-stage process. Rather than altering the compression ratio over numerous stages, the authors have devised a conversion process that exerted a constant compression ratio over the foam at precisely timed intervals at specified temperatures.

The process was split into three separate stages. Firstly, the foam was inserted into the mould, which exerted a predetermined compression ratio over the sample, and placed into the oven at a specified temperature for a specified time. The mould was removed from the oven and the foam removed from the mould and stretched lightly by hand in all directions. This helped to prevent the adhesion of cell ribs. The whole first stage was then repeated, which was the second stage. For the third stage or annealing stage, the foam was placed back into the mould and into the oven at usually a considerably lower temperature and for a shorter amount of time.

2.2.8. Issues with the Thermo-mechanical Fabrication Process

For the purpose of this study, investigating the thermo-mechanical conversion process was essential in order to replicate the method and develop auxetic foams, however the literature available offered little consistency in key parameters of the conversion process; temperature, time and volumetric compression, despite comparable conventional foams being used (Table 2.2 and table 2.3). It is significant that researchers using supposedly similar conversion methods result in huge variations in resultant auxetic foams and on closer inspection, variables of the fabrication process can range dramatically between studies. For example, annealing time alone ranges between 10 and 60 minutes between key authors (Table 2.3). When scrutinising the studies that have successfully developed auxetic foam, there appears to be little agreement between academics as to which stages of the conversion process are most imperative to ensure negative Poisson's ratio in the resultant foam. Li and Zeng (2016) described the current approach to developing auxetic PU foams as a 'trial and error' process and attempted to address this issue by investigating the chemical composition, microstructure and thermomechanical properties of three different PU foams with similar morphology and converting them into auxetic foams using the thermo-mechanical method. By doing so, they were able to adapt the fabrication process in the context of the chemical properties of the PU foams. They found that an understanding of fundamental material chemistry of the conventional foam was imperative to auxetic conversion consistency.

'Stress induced deformation and relaxation of SAN particles' in the PU foam was found to be an influential mechanism to successful conversion. This therefore suggests that volumetric compression followed by relaxation stages were highly influential and therefore heating and annealing temperatures and time constraints will vary depending upon the conventional foam used and the conclusion can be drawn that there is not one significant variable to ensure a successful conversion process. Rather, the conversion process and variables are heavily dependent upon the material utilised in the fabrication process and a true understanding of the material properties will facilitate a more predictable auxetic structure.

In terms of this research study, it was therefore essential to develop a fabrication process from studies that utilised similar PU foams. Although it would have been ideal to carry out a complete chemical analysis of the starting foam, due to time constraints this was not possible and therefore bearing in mind the study by Li and Zeng (2016), a 'best-fit' approach of conversion methods in available literature had to be adopted.

2.2.9. Thermo-Mechanical Method Used in This Study

There is scope for the present study to implement a similar conversion method to those developed by Gatt et al. (2011), Sanami et al. (2014) and Allen et al. (2015b) as the starting foam used for this study is of similar specifications. The exact conversion method is described in the methodology chapter, chapter 3. Tables 2.1 and 2.2 provide an overview of the key fabrication processes from three authors that this research uses as a base to develop a similar process.

Table 2.1 Foam specifications from key studies utilising the multi-stage thermo-mechanical method							
Author	Foam density (Kgm3)	Pores per inch (ppi)	Material	Starting dimensions (mm)	Converted dimensions (mm)	Linear compression Ratio (LCR)	Poisson's Ratio (v)
Gatt et al. (2011)	Information not provided	30	Polyurethane ether open cell	29 x 29 x 68	22 x 22 x 50	0.69	Information not provided
Allen et al. (2015b)	26-32	30, 45 and 60	Polyurethane open cell	118 x 118 x 118 143 x 143 x143	100 x 100 x 100 100 x 100 x 100	0.85 and 0.7	-0.07 at 10% strain
Sanami et al. (2014)	26-32	45	Polyurethane open cell	100 x 100 x 100	65 x 67 x 67	0.67	-0.22 at 15% strain

Table.2.2 Individual conversion processes of key authors to this study				
Author	Preparation	Stage one (heating)	Stage two (heating)	Stage three (annealing)
Gatt et al. (2011)	Mould was lubricated.	The mould containing the foam was inserted into an oven at 200c for 10 minutes, the foam mould was removed from the oven and the foam allowed to cool at room temperature whilst still in the mould. Once cooled, the foam was removed and stretched by hand to avoid adhesion of cell ribs.	Stage one was repeated.	The mould containing the foam was re-inserted into the oven at 200c but instead for 60 minutes.
Allen et al. (2015b)	The foams were inserted into the compression mould. A lubricant was used to reduce surface creasing.	The mould was inserted into the oven at 200c for 30 minutes. The mould was removed after 30 minutes and the foam was stretched in all directions by hand, gently, at room temperature.	Stage one was repeated.	The foam was placed back into the mould and into the oven at 100c for 30 minutes. The foam was removed and stretched gently by hand at room temperature.

Sanami et al. (2014)	None specified.	The mould was inserted into the oven at 190c for 50 minutes. The foam was removed from the mould and stretched by hand at room temperature.	The mould containing the foam was placed back into the oven at 190c for 20 minutes. The foam was removed from the mould and stretched by hand at room temperature.	The foam was placed back into the mould and reinserted into the oven at 100c for just 10 minutes. The foam was removed from the mould and stretched by hand at room temperature.

Researchers (Chan and Evans, 1997) have discovered that adjusting the volumetric compression values during production directly increases or decreases the negative value of Poisson's ratio. Thus, a selection of auxetic foams were produced by experimenting with the compression process, with varying density and varying negative values of Poisson's ratio. Interestingly, this indicates that it is possible to develop auxetic polymeric foam to desired auxetic specifications depending upon the end use. This study should allow the preliminary development of unique auxetic foams to be established first, doing this preliminary work should then permit future research which develops specifically tailored auxetic foams for competitive aquatic watersports.

It is therefore imperative to understand how the negative Poisson's ratio value can affect the mechanical behaviour of the foam. It is relevant at this point to acknowledge that polymeric foams are commonly utilised in situations where cushioning or resistance to impact is an important feature (Chan and Evans, 1998). Therefore, the focus of many studies that have developed or examined auxetic foams has been to ascertain whether their unconventional characteristics allow them to exhibit enhanced impact resilience and crashworthiness features. One of the focuses for this study is to research how the enhanced mechanical properties of auxetic foam may be suitable for use in water sport protection vests. In order to do so, an investigation into the mechanical properties of auxetic foams for impact resistance has been conducted. Before investigating these properties, firstly the 'role' of an impact protection vest needs to be established from current market models, this then enables the research on auxetic foam to be assessed clearly with the end product specifications in mind.

2. 3. The Mechanical Properties of Auxetic Foams

Auxetic foams are increasingly being developed for a range of sporting applications and although no papers at the time of this research were specifically dedicated to the application of competitive watersports, this section will aim to gather the information available and present it in a way that is linked to the application of competitive water sport activities.

2.3.1. The Potential of Auxetic Foams in Water sport Protection Vests

Impact protection vests by their very nature are required to protect the wearer from high-speed impacts with water and water sport equipment. For the purpose of this study, protection vests for competitive sports such as kitesurfing and windsurfing are considered.

In order to assess the potential for the utilisation of auxetic foams in water sport protection vests, the key performance features of such products has to be identified. Although it is assumed that first and foremost, the main function of the vest is to protect against impact, other features may also be important. Table 2.3 highlights the key performance features of water sport protection vests that are marketed by O'Neill and Body Glove. From the information gathered for table 2.3, it is apparent that the key performance features can be disseminated into a collection of specific material features. This study has identified them into three categories; 1) protection against impact, 2) freedom of movement and 3) favouring lightweight material. Table 2.4 illustrates how the key material performance features identified are disseminated into the three main material characteristics. In the context of this study, in order for the auxetic foams produced to provide a combination of the three key elements listed above, it is predicted that they will have to be produced of varying degrees of thickness to assess whether thinner foams offer lightweight freedom of movement but also adequate resistance to impact for example. As discussed in section 2.2, developing thicker cuboidal auxetic samples is preferable as the tri-axial compression ratio over the foam in the mould can be more accurately predicted and maintained, thus theoretically producing a more homogenous sample. Other researches then go on to slice thinner samples as appropriate (Duncan et al, 2016a). It was found when conducting this study that the thinnest auxetic specimen without slicing the converted foam into smaller dimensions, was developed by Duncan et al (2016b) by utilising through pins in the mould to reduce surface creasing.

However, the sample was still considered too thick (30mm) for the purpose of this research and therefore producing thicker samples and slicing them into smaller, thinner samples is considered the most appropriate method.

Table.2.3 Identification of Impact Vest Key Performance Features			
Brand	Product Name	Key Performance Features	References
O'Neill	Gooru technobutter competition vest. Approximately: £99.95	• Segmented foam core • '30% lighter' • Quick drying, '20%' less water absorption • 'anatomical flex points' • Super stretch Technobutter neoprene • Advanced impact protection material	(Abersochwatersports 2016; O'Neill 2016)
Body Glove	Prime comp Vest approximately: £100	• Specific panels allow flexibility and movement • 'Poron XRD' impact material • Lightweight material • Strategic 'drain panels'	(Body Glove, 2016)

Table 2.4 Three Main Material Characteristics of a Water sport Protection Vest			
Brand and key performance features	Key Material Characteristics		
	Impact protection	Freedom of movement	Lightweight
O'Neil Abersochwatersports 2016; O'Neill 2016)	• Advanced impact protection material	• 'anatomical flex points' • Super stretch Technobutter neoprene • Segmented foam core	• '30% lighter' • Quick drying, '20%' less water absorption
Body Glove (Body Glove, 2016)	• Poron XRD' impact material	• Specific panels allow flexibility and movement	• Lightweight material • Strategic 'drain panels'

2.3.2. Impact Protection and Lightweight Materials

When collating the impact protection vest material characteristics highlighted in table 2.4, it is evident that advanced materials are the main feature to provide maximum protection from impact. It is assumed that heavy protective material can be restrictive and therefore this is why a lightweight, protective material is crucial. It is apparent from the table 2.4 that a lightweight material is key to athletic performance and interestingly, the brands use different ways to achieve this. For example through the use of quick drying material to reduce water absorption and strategic water-draining garment design. It is clear that reducing the weight of the protective vest by reducing the amount of water the material absorbs, can help to significantly reduce the weight of the overall garment. Therefore, these factors should be a consideration when appraising auxetic materials for their suitability for water sport impact protection vests.

2.3.3. Freedom of Movement

In the context of this study, competitive water sports such as kitesurfing and windsurfing by their very nature require dynamic movement from the athlete. Therefore, the material used in the protective vest is required to provide maximum protection but also allow maximum body movement. The information presented in table 2.4 shows commercial impact vests currently on the market at the time of this study to have features such as flexibility panels and segments made from elastomeric fabrics to enable high range of movement.

2.3.4. Auxetic Foam Properties: Impact Resistance

Chan and Evans (1998) examined the resilience to indentation of polyurethane auxetic foams in comparison to conventional foams and found the auxetic foams to display higher resistance. However, it is important to consider that the conversion process of auxetic foams increases the foam density and increased density can improve resistance against impacts. However, Scarpa et al. (2005) investigated this characteristic and confirmed that the increased density of NPR foams was a contributing factor to improved impact resistance but that the nature of the auxetic structure itself was the main reason for increased resistance. Assessing stress-strain relationships of auxetic and conventional foams under typical quasi-static compression testing further illustrates this point, figure 2.2 taken from Allen et al. (2015b) can be used as an example of this behaviour. A typical stress-strain relationship for conventional foam displays a reasonably linear behaviour at low strains, in this case up to ~5%, which is then followed by a plateau region. This is because conventional foam cells typically collapse under compressive strain, even a particularly dense foam that improves resistance to impact would collapse under compression. Auxetic foams on the other hand display a very different stress-strain relationship. Due to auxetic foam cells contracting under compression, the stress-strain relationship of auxetic foam remains linear.

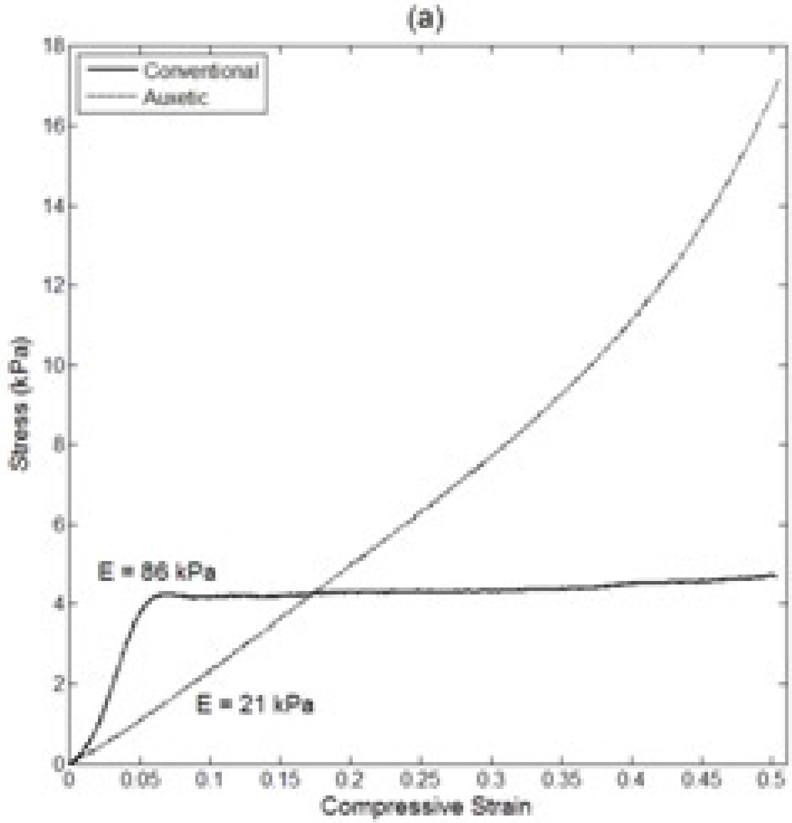


Figure 2.2 Stress-strain relationship of auxetic and conventional foam under typical quasi-static compression (Allen et al. 2015)

Under impact, Chan and Evans (1998) found that conventional foam displayed more 'local' indentation whereas the auxetic foam exhibited a much broader area of indentation. They concluded that this was due to the inherent behaviour of auxetic materials under pressure; they suggested that the layer directly under the indentation is compressed and then the subsequent layer underneath the initial impact area is drawn in to support the impact point, which increases density and therefore increases the resistance to indentation. On the other hand, conventional foams under indentation act differently. The indentation impact causes the material layer under compression to be drawn away from the impact, reducing the density of the solid, thus leading to the cell structure collapsing.

Similar studies by Scarpa et al. (2002) and more recently Sanami et al. (2014) have also demonstrated that auxetic polyurethane foam exhibits more indentation resistance compared with conventional foam because it absorbs more of the 'indentation energy'. Scarpa et al. (2002) examined auxetic polymeric foams under high strain dynamic crushing (over 20kN) for suitability to crashworthiness applications. In comparison to conventional foam, the auxetic foam displayed strong resistance to very high strains. This suggests that conventional, common foam used for packaging, could be converted to auxetic using a relatively simple conversion process and used in high impact applications. Other researchers have tested auxetic foams at lower impact levels suitable in sports protection environments and found similar improved resistance. Sanami et al. (2014) found that the indenter load had to be much higher, more than twice the amount used to deform the conventional foam by 10mm. Allen et al. (2015a) tested both auxetic and conventional foam up to 5.6j impacts and found the auxetic foam to experience peak impacts of three times lower value than conventional foam. This is significant because foams used in impact protection vests for watersports may experience a combination of both high and low impact strains, therefore it is relevant to acknowledge that auxetic foams have previously shown to reduce impact in both cases. A lightweight material was also favoured by market leading brands in water sport protection vests, as highlighted and discussed above in section 2.3.1. In line with this, it is also predicted that smaller samples of auxetic foams compared to that required by conventional foams will protect the wearer effectively, thus having the potential to produce a garment that is lighter in weight. These predictions were assessed further using primary research methods.

Furthermore, Chan and Evans (1998) also found that the more negative the value of Poisson's ratio was, the more resistance occurred during the indentation event and in addition, found that the level of impact resistance began to increase more rapidly with the increase in magnitude of the indentation force. Understanding both of these consequential behaviours and by utilising the multiple stage compression process generates the possibility of developing auxetic foams that are finely tailored to their end application. However, developing initial auxetic foam specimens is the focus of this research, further defining the process to tailor auxetic foam should be the focus of further research.

2.3.5. Auxetic Foam Mechanical Properties: Synclastic Curvature

Harbouring a synclastic curvature could enhance athlete performance in the context of an impact protection vest and a compressive wetsuit. Auxetic materials are known to exhibit a synclastic curvature, though little literature can be found that examined this behaviour for a specific application (Alderson and Alderson 2007; Lisiecki et al. 2010). Though it has not yet been widely researched, the synclastic curvature ability of auxetic foams has been investigated or recommended for other applications. For example, Alderson and Alderson (2007) recommended the suitability of auxetic composites and foams to aerospace technologies. The shape of an aircraft requires complex curves, for example in the nose cone, and auxetic materials display a synclastic curvature which eliminates the need for heavy machining to curve the material resulting in possible damage.

In the perspective of a wetsuit, a compressive wetsuit is designed to hug body contours and fit close to the body. The effect of a contoured body shape on hydrodynamic resistance is discussed across section 2.6 and 2.7. However, it is appropriate to highlight at this point that it is well-known that reducing hydrodynamic resistance with a compressive wetsuit can consequently improve athletic performance. Therefore in relation to this study, as the human body is a complex shape of many curves and cylindrical shapes, auxetic foams in theory have the potential to conform to these shapes more effectively than conventional materials with a positive Poisson's ratio and as a result could reduce hydrodynamic resistance in a sporting situation. In the context of an impact protection vest, it is essential for the athlete to be protected to maximum levels but also to be able to move dynamically as required, as auxetic foams may be more suited to fitting human body contours, it is hypothesised that they will provide improved flexibility when worn on the body, rather than restrict during movement. These behaviours are theoretical and have not been examined at the time of conducting this research and therefore this study aims to investigate this properties further and provide preliminary research on this topic. Primary research methods were used to further investigate these predictions.

2. 4. Structural Auxetic Textiles and Yarns

Developing auxetic textiles using a variety of different manufacturing methods helps to broaden their potential utilisation. Hu et al. (2011) specifically notes some of their novel uses in textiles such as; fabrics that change colour under uniaxial strain, blast-protection clothing, dental floss with drugs incorporated that are released with movement and slippage prevention in thread knots. In order to assess the suitability of structural auxetic textiles to competitive swimming, the various manufacturing techniques and resultant fabric properties are discussed. Potential properties and behaviours of structural auxetic textiles are then assessed for their suitability to competitive swimsuit application. The conclusion of potential usage in competitive swimwear will be theoretical as auxetic textile structures are complicated to manufacture and for the purpose of this research, are not suitable for practical development due to time restrictions. However, the following critical review of auxetic structural yarn and textiles is designed to inform future research in this area. Auxetic polymeric foams on the other hand are more straightforward to manufacture and their potential benefits to outdoor competitive swimming wet suits and impact protection vests for water sports are the main practical developments of this research. As the auxetic foam is examined for use within a garment, the test results should give some indication of the general negative Poisson's ratio response to being worn on the human body to enhance competitive swimming and therefore should indicate suitability of auxetic textiles to enhance competitive indoor swimming.

2.4.1. Structural Auxetic Yarn

Auxetic yarn has been developed utilising conventional polymeric fibres into a helical formation to provide the auxetic effect, resulting in a negative Poisson's ratio. The Helical Auxetic Yarn (HAY) structure was first characterised and developed by Professor Hook in 2003 (Hook 2003 in Wright et al. 2012). Some researchers use the term Double Helix Yarn or DHY to describe a yarn produced with the same manufacturing process as HAY. An elastic, low modulus thin 'wrap' fibre is systematically wound around a higher modulus thick compliant core fibre. Once the yarn is extended in the longitudinal direction, the compliant core displaces the wrap fibre due to the difference in elastic modulus and diameter of the fibres and creates a helical arrangement. This consequently produces the lateral increase in dimension, which is the essential mechanical engineering behind the expansion behaviour when an auxetic material is extended (Sloan et al. 2011; Wright et al. 2012; Bhattacharya et al. 2014).

The original manufacturing process of the HAY has generally remained the same, though some scientists have used slight modifications of the original HAY manufacturing process to produce different variants of the Helical Auxetic Yarn, nevertheless the concept has remained largely the same. For example, rather than wrapping the fibres, Lim (2014) permanently stitched the thinner 'wrap' fibre into the core fibre, which as a result creating a semi-auxetic yarn. During longitudinal strain loading, the yarn has an auxetic plane and a conventional plane. The research is designed to highlight the main fibre parameters that affect the positive and negative Poisson ratio values of the resultant yarn. In the semi-auxetic yarn, geometry requires the thin cord to be stitched in a triangle formation and the author suggests other auxetic geometries may be suitable for producing similar semi-auxetic yarns and subsequent manufacturing techniques. It was found that the primary focus of research in this area of auxetic textiles is to determine and improve the manufacturing parameters and geometric properties of the yarn that have a direct influence on the negative Poisson's ratio value, rather than knitting or weaving the yarn. This is most likely due to this research area being novel and under-developed.

Sloan et al. (2011) developed Helical Auxetic Yarns intended for use within textiles. They investigated two geometric properties of the yarn structure; the starting angle that the wrap fibre is spun around the core fibre and both the diameter ratio of wrap fibre to core fibre and their resulting relationship to the auxetic effect of the yarn. When analysing both parameters, the numerical value of negative Poisson's ratio demonstrated to be more receptive to the angle of the wrap fibre in comparison to the relationship between fibre diameters. The study also found that the original Poisson's ratio of the wrap and core fibres when tested separately had an influence on the overall mechanics of the Helical Auxetic Yarn (HAY). The yarn harboured a negative Poisson's ratio as large as -2.7. Similar studies by Wright et al. (2012) and Bhattacharya et al. (2014) also supported the importance of the relationship between wrap angle and auxetic effect. Wright et al. (2012) found that lowering the wrap angle around the core resulted in a lower force being required to stimulate the on-set of auxetic behaviour; this is because strain on the yarn occurs earlier in comparison to yarn produced with a higher wrap angle. Bhattacharya et al. (2014) produced all of their samples with a low, 12 degree wrap angle. Their study aimed to determine the optimum moduli comparison of the core and wrap fibres to prevent the indentation of the core fibre and the yarn they produced displayed a large negative Poisson's ratio of -13.52. They found that indentation occurs when the wrap fibre is too stiff in comparison to the core fibre. Instead of creating the desired helical orientation, the wrap fibre lodges itself into the core fibre causing indentation and thus significantly reducing the auxetic event. The work by Bhattacharya et al. (2014) has built on this foundation by specifying optimum moduli of the fibres to prevent indentation and developing a yarn with a high NPR, thus creating the ability to engineer tailored auxetic yarns in the future. However, development of such yarns into auxetic fabrics is limited at this time, which consequently limits their suitability to this research.

The helical auxetic yarn is considered by academics as one of the most promising developments for exploitation of auxetic behaviour in applications (Wright et al. 2012). Despite its potential, few examples of the textile fabrication of auxetic yarns have been recorded. Of the samples that have been documented, there are performance issues. Miller et al. (2009) were the first reported researchers to develop an auxetic composite with potential low-modulus employment such as automotive and aerospace applications. The auxetic yarns were woven in a plain weave construction in the weft direction with the warp yarn being a conventional yarn. In a single layer composite however, the yarns would overlap out of plane under extension, causing a positive value in-plane Poisson's ratio but a negative out of plane Poisson's ratio. Introducing a second layer to the composite provided more constraint within the structure and maintained the negative Poisson's ratio in-plane. An NPR value of -0.1 was recorded. Wright et al. (2012) similarly found out of plane negative Poisson's ratio to occur in woven auxetic fabrics. Wright et al. (2012) experimented with different helical auxetic yarn types to subsequently develop into low tensile modulus fabrics, suitable for healthcare compression bandages and support garments. However, the textile samples produced were still considered unsuitable for the purpose of this research as it is predicted that compression swimsuits require a higher modulus textile than that created by wright et al. (2012). The fabrics were constructed in a plain weave geometry with the HAY running in the warp direction and conventional yarn in the weft. One of the fabrics exhibited a negative Poisson's ratio out of plane due to the weft yarn characteristics. The most reliable sample exhibited a NPR in-plane between strains of 15% up to 40%, the highest negative Poisson's ratio value being -0.1.

The current developments of auxetic textiles produced from helical auxetic yarns offers promising insights, but results are limited as the available research is on a small experimental scale. Both Miller et al. (2009) and Wright et al. (2012) developed very narrow woven textile samples that were not tested for performance and manufacturing consistency in a larger sample. For this reason and for the purpose of this project, the development of auxetic fabrics from helical auxetic yarns are considered to be less advanced than other areas of development, such as the development of auxetic foams.

2.4.2. Structural Auxetic Textiles

There is more research available to support the development of auxetic textiles using conventional yarns in an auxetic structure, in comparison to producing auxetic fabrics from helical auxetic yarns. This could be because knitting as a manufacturing technique is much more versatile than weaving textiles. Thus, structural auxetic textiles have been manufactured based upon different auxetic geometries.

When Ugbolue et al. (2010) researched the possibility of warp-knitting an auxetic textile material, they split their work over a series of research papers. They claimed that at the time of writing their journal, there had been previous attempts at fabricating auxetic textile materials without success due to the complicated nature of such fabrics. On the other hand, their research presents a theoretical analysis of ideal geometric properties along with a practical development of the auxetic textile, utilising the honeycomb (hexagonal) formation. At the time of publication they concluded, warp-knitting was the most effective way to manufacture structural auxetic textile materials (Ugbolue et al. 2011). Out of the selection of fabrics that they developed, all of them were auxetic in both directions; in the weft direction up to 30% extension and in the warp direction from 30% and over. The highest extension with a negative Poisson's ratio in the weft direction was 31% with an NPR of -0.05 and in the warp direction 67% and -0.03 Ugbolue et al. 2011). As the fabric is extended to a higher strain level; the NPR value becomes small and eventually reverts to a positive Poisson ratio. However, the fabric samples that they produced show promising results, they are able to remain auxetic under considerable strain, possibly indicating their suitability to being used in high performance purposes, such as competitive swimming. Whereas some textiles produced have only been proven to be auxetic at low strains, like the work by Alderson et al. (2012) for example and therefore may not be as well suited to an end use such as competitive swimming.

Alderson et al. (2012) developed warp knitted auxetic textiles by examining different variations of the re-entrant triangle structure formation. They produced fabrics that were only auxetic diagonal (-45 degrees and +45 degrees) to the warp direction but they were designed to remain auxetic and were not simply one-stretch auxetic fabrics as have been developed by other academics. However, they only examined the Poisson's ratio of the fabrics at low strains of 0.5% and 10% extension but found each of the fabrics to remain auxetic and they predicted that the structure would continue to display a negative Poisson's ratio at higher levels of extension. They predicted that the fabrics would begin to display a positive Poisson's ratio value, as seen in the work by Ugbolue et al. (2011). This was predicted to happen at some point during increased strain but indicated it would be at a much higher value than 10%. However, no specific value was given as it was out of the scope of the study at the time of publication (Alderson et al. 2012).

Contrary to Ugbolue et al. (2010), advising that warp-knitted designs were the most appropriate to manufacture auxetic fabrics, other academics have successfully produced weft-knitted auxetic fabrics. This indicates the growth in research momentum in this area and the possibilities for future development. Hu et al. (2011) successfully produced a variety of weft-knitted auxetic textiles on a flat knitting machine using three different geometrical structures; re-entrant hexagon (honeycomb), rotating rectangle and a foldable structure, all of which are geometrical structures known to produce the auxetic effect. All of the structures, apart from the extreme folded structure, displayed an immediate decrease in auxetic effect upon the increase of strain, indicating once again that the Poisson ratio value would turn positive at a certain point when loading strain. All of the fabrics were auxetic in both warp and weft directions. However, the extreme folded structure does not uniquely remain auxetic under high strain levels, the same decrease in auxetic effect is witnessed but at a later stage of extension. This is because more force over a longer period of time is required to open up the folds of the structure. In a similar development, Glazzard and Breedon (2014), more recently developed a weft-knitted auxetic textile based upon the double arrowhead geometric structure. The structure was a folded structure that again unfolded under strain. The fabric developed was auxetic in both the weft and warp directions.

2. 5. Potential Application of Auxetic Textiles to Indoor Competitive Swimming

Research suggests that knitted structural auxetic textiles experience the onset of a positive Poisson's ratio at high strains, the point at which this happens is dependent upon various factors such as auxetic geometry, yarn moduli and strain level. For example, Alderson et al. (2012) confirmed that the modulus of the fibres used in their re-entrant triangle formation, specifically for the stabilising component, would largely dictate the modulus of the overall textile due to the structural response to strain. It has already been acknowledged that compression wear for athletic purposes is required to have high levels of extension and recovery, providing the athlete with a second skin feel (Shishoo 2005; Wu, 2011). At the time that this research was conducted, auxetic structural textiles had not been examined under high extension and recovery conditions for use in compression wear, most likely because the structures would revert to positive Poisson's ratio and are therefore not developed any further within the primary research of this study. Future research to develop auxetic structural textiles for competitive swimwear should therefore focus on merging the optimum combination of yarn geometry and yarn moduli in order to remain auxetic at high strains.

Research suggests that conventional knitted fabrics have been gaining momentum in use in many technical textile applications such as; sports, automotive, aerospace, protective and military textiles and are highlighted as specifically suitable to compression wear (Gokarneshan et al. 2011; Wardiningsih et al. 2013). As highlighted in section 2.2.1, a small independent study supported that warp knitted fabric may exhibit a small amount of surface roughness suitable for manipulating flow thus reducing hydrodynamic resistance (Moria et al. 2011). It is therefore suggested that warp knitted auxetic textiles could potentially be the most suitable construction for indoor competitive swimwear and should therefore be the focus of future development within this area.

Although the primary research conducted for this study investigates auxetic foams for competitive outdoor wetsuits, the conclusions made from the primary research should provide strong indications of the potential behaviour of developing auxetic textiles for use within indoor competitive swimming garments.

2. 6. The Fluid Mechanics of Human Swimming

This section sought to gain an understanding of current literature focused on the factors that affect human swimming. This is in line with aim two of this study, to analyse contextual factors that influence the performance of athletes in competitive aquatic sports. Once these factors have been identified, auxetic materials can then be investigated for their potential in competitive swimming.

2.6.1. Factors that Influence Swimming Performance

Hydrodynamic drag is a major counteracting force during competitive swimming, the resistance of a body moving through water experiences is estimated as 500-600 times more than a body moving through air (Taiar et al. 1999). Therefore reducing the hydrodynamic resistance acting upon the swimmer can significantly improve swimming performance. It is acknowledged that the main contributing factor to an athlete's overall swimming performance is the swimmer's fitness ability and technique. Hydrodynamic resistance is subsequently considered to occupy '90%' of a swimmer's power output. (Mollendorf et al. 2004; Pendergast et al. 2006; Moria et al. 2010).

2.6.2. Swimming Velocity

The higher the velocity of a swimmer, the quicker the race will be competed. Swimming velocity is dependent on two main factors, the hydrodynamic resistance that is resisting the forward movement of the swimmer and the athlete's propelling vector force. Increasing the propelling force and decreasing the hydrodynamic resistance is the key to improving a swimmer's performance (Marinho et al. 2012). Alongside swimming technique and adequate training, a competitive swimsuit may help to reduce the hydrodynamic resistance and subsequently improve swimming performance (Pendergast, et al. 2006). Research (Blazevich 2010; Voyce et al. 2010; Wu, 2011) suggests that competitive (racing) swimsuits are designed to enhance swimming performance. There has been significant research dedicated to this area of study in recent years, though the relationship between swimsuits and fluid mechanics of an athlete is still not considered to be well-understood (Moria et al. 2011). In order to consider how auxetic materials may benefit swimming performance, the relationship between hydrodynamic resistance and conventional swimming materials must first be established.

2.6.3. Hydrodynamic Resistance

The resistance that is acting against an athlete during forward motion in air or water, such as swimming, cycling or sprinting is the drag force. Hydrodynamic resistance is highly correlated to the swimmers unique body shape and the water flow characteristics (Mollendorf et al. 2004; Naemi et al. 2010). When studying fluid mechanics, the total force of hydrodynamic resistance that is acting upon an athlete during swimming consists of a combination of three components: friction drag (Dsf) wave drag (Dw) and pressure drag (Dp) (Mollendorf et al. 2004; pendergast et al. 2006; Geer et al. 2012). Therefore, the total body resistance (D) can be assumed as:

$$D = (Dsf) + (Dw) + (Dp) \tag{1}$$

During active swimming, all three components are responsible for a percentage of the total drag, however during passive swimming wave drag can be close to non-existent (Bixler et al. 2007; Wu, 2011).

Both passive and active drag are two distinguished categories of hydrodynamic resistance. Active drag is the resistance experienced when an athlete is actively propelling themselves (swimming) through the water due to the dynamic change in shape. Passive drag is experienced when an athlete is in a fixed position and is moving through the water below 0.5m, for example during the gliding part of the swimming race after the athlete has dived into the water or after a tumble turn (Pendergast et al. 2006; Naemi et al. 2010). When an athlete is propelling against the resistance of active drag, they are experiencing a force of a higher magnitude in comparison to that of passive drag, this is because when actively swimming, the body is creating an alternating shape whilst propelling forward, rather than remaining as streamlined as possible (Mollendorf et al. 2004).

In the study of fluid mechanics, it can be complicated to measure the relationship between hydrodynamic resistance and competitive swimsuit material during the active drag phase of an athlete swimming; therefore, many studies assess this relationship during passive drag. This examination technique is supported by many researchers as it helps to eliminate as closely as possible the potential of variation due to the human influence of swimmer technique and instead seeks to examine the suit or fabric exclusively (Mollendorf et al. 2004; Pendergast et al. 2006; Abasi et al. 2013).

Friction drag, wave drag and pressure drag each have varying degrees of influence on the total drag force, however, pressure drag or form drag and wave drag are considered the most significant types of hydrodynamic resistance during competitive swimming. However, academics agree that despite being considered less influential, a reduction in skin friction can create significant competitive advantage during competitive swimming (Pendergast et al. 2006; Blazevich, 2010; Moria et al. 2010; Geer et al. 2012).

Pressure or form drag is a direct relation to the resistance created by the shape of the body moving through the water. Surface resistance or skin friction is the shear force interaction between the surface of the body or wetted area and the fluid. Wave drag is the force required to create waves, which mainly occurs at the water air interface, which in consequence, explains why little or no wave drag is experienced during gliding parts of the race as the athlete is submerged with their arms and legs stationary, rather than making propulsive movements. Energy wasted on making waves results in less energy dedicated to propulsive forward momentum (Douglas, 2005; Blazevich, 2010; Moria et al. 2010; Naemi et al. 2010; Geer et al. 2012).

2. 7. Swimsuit Material Characteristics That Reduce Hydrodynamic Resistance

The following section works to critically appraise the drag reducing properties of swimsuit materials. Generally, the work can be divided into two significant categories of research. The first is the exploration of material surface properties and their resultant influence over friction (skin) resistance and the second relates to the compression of the swimsuit on the body and its relationship to pressure drag and wave drag. In general, researching the utilisation of a swimsuit to reduce pressure drag and skin friction, tends to be dominant in the study area. For the purpose of this research it is assumed that this is because, as highlighted earlier, most academics have studied the mechanical properties of swimsuit material during passive drag conditions in order to eliminate human influence during testing and wave drag is mainly present during propulsive swimming near to the water's surface.

It is important to note that many of the studies published in this area of academic research have been either funded or supported in some respect by swimming brands or manufacturers;

this has been highlighted where background information has been made available and where the information is applicable throughout this study. In the context of this research, depending upon the nature of the research undertaken, support from a swim brand could present a bias set of research results, or on the other hand, a body of knowledge created by experts in this particular field. Research in this area also usually features small-scale participant groups as competitive swimmers do not represent a high majority of the population.

2.7.1. Skin Friction Resistance

Some academics (Toussaint et al. 2002) claim that the skin resistance (surface resistance) of a swimsuit has a minimum contribution to the overall value of hydrodynamic resistance and therefore ‘smooth’ friction-resisting textiles can only offer a very small reduction in drag and to the reader, it appears to be consequently disregarded within their work. On the other hand, it is more heavily supported by other academics (Bixler et al. 2007; and Wu 2011) that skin resistance should not be regarded as irrelevant particularly where wave drag is negligible during the gliding stage when experiencing passive drag. Bixler et al. (2007) used an accurate Computational Fluid Dynamics (CFD) model as an outlet to examine the effect of passive hydrodynamic drag on a swimmer during the glide phase of swimming. Based on the assumption that the swimmer in the experiment had zero surface roughness, the friction resistance was found to represent 25%-27% of total drag at relevant competitive swimming velocities. If the athlete’s surface roughness increases, so will the drag amount. They also found that once the swimmer is closer to the water air interface where wave drag becomes significant, the wetted area of the swimmer reduces thus leading to a reduction in surface resistance percentage of total drag, though the actual amount of reduction was not given. They further estimate that the gliding phase during a race accounts for approximately 15% of the total race. This may seem a trivial fraction of the overall swimming routine, perhaps confirming surface friction as insignificant. However, swimming is a highly competitive sport where very small time margins distinguish between winning and losing (Blazevich 2010; Moria et al. 2010). Therefore, it is assumed that reducing resistance for just 15% of the total race could create competitive advantage. The study was part-supported by Speedo UK, indicating that the research was conducted with close industry ties and perhaps further validating the study. Similarly other academics (Cortesi et al. 2014) found material properties of swimsuits to reduce drag more significantly than any other attribute, for example the ability to improve body position in the water by lifting the lower limbs. With technical assistance from the Arena swim brand, Cortesi et al. (2014) found full body polyurethane (neoprene) swimsuits to have reduced friction resistance compared to a full body textile and brief suits. Furthermore, the results indicate that not only is fabric selection important but also body coverage. However again, the specific material properties that can reduce surface resistance were not explored. For the purpose of this research, understanding material properties and their influence on friction resistance is key to developing auxetic materials suitable for competitive swimming. However, few studies were found to have researched this information.

The studies by key academics in this area (Rogowski et al. 2006; Moria et al. 2011; Abasi et al. 2013) highlight both macro and micro level material surface characteristics that can reduce hydrodynamic drag. Abasi et al. (2013) examined the drag resistance of different fabric compositions as a 'creased' sample and a smooth sample on a manikin. Although limitations of using manikins have been discussed, in this instance the researchers benefitted from being able to isolate friction resistance from other factors. The creased sample counterpart significantly increased the hydrodynamic resistance in every case in comparison to the smooth sample as it created a larger surface area for the water to travel over. Other researchers (Naemi et al. 2010) support that manufacturing swimsuits to be form fitting will create a smooth surface, thus reducing surface resistance.

Theoretically, due to their positive Poisson's ratio, conventional textiles and foams will bulk or crease with joint movements, whereas auxetic fabrics on the other hand do not 'bulk' under stress and instead they contract as they harbour a NPR. Therefore, auxetic textiles and foams should reduce creasing, thus potentially reducing surface drag during competitive swimming.

In the context of this study, the research conducted by Abasi et al. (2013) proved that the swimsuit should generally be smooth and tight fitting and not harbour any surface creasing in order to decrease resistance, which is agreed with other academics (Naemi et al. 2010). Yet, when studying flow transition, the theory suggests that for an object that is considered streamlined, if the surface is rough, the surface (friction) resistance will increase and therefore a smooth surface is optimal. However, for shapes that are not inherently streamlined, for example, cylindrical, spherical shapes and the human body, it is well known that in some cases that initiating turbulence in the boundary layer can actually reduce the overall drag by helping the flow remain attached to the surface, rather than separating (Moria et al. 2011). A well-known example of this is a golf ball, the indentations cause the boundary layer to experience a higher momentum due to the turbulence created and as a result, resist separation to turbulent flow beyond the boundary layer for longer (Naemi et al. 2010). Concurring with this theory, an independent study without brand sponsorship by Moria et al. (2011), examined the aerodynamic properties of five different technical swimsuit fabrics by various different swim brands. Overall, they found a certain degree of surface roughness, a result of the fabric construction, could manipulate the air flow transition over the fabric and create a reduction in aerodynamic efficiency, which can then be translated into an advantageous reduction in hydrodynamic resistance during swimming. The Spalding and Speedo Fastskin II fabrics examined in the study both showed the early transition phases and although fabric construction is not stated, both fabrics appear to be warp knitted from the microscopic pictures in the research journal. This indicates that knitted fabrics have drag reducing surface characteristics, as they have a more rough surface compared to woven fabrics. In the context of this study, and in regards to the literature reviewed on auxetic textiles, this information is an encouraging lead to further explore the potential of knitted auxetic fabrics for competitive swimming. Although as previously stated, this research only considers auxetic textiles on a theoretical basis and no primary research towards this was undertaken, though it is highlighted as a possible avenue for future research.

Although, the reduction due to the apparent surface roughness was not necessarily very large, Moria et al. (2011) recommend that a combination of textile fabrics could help to create this early flow-transition advantage. However, they do not specify where in particular the rougher fabrics should be placed on the body. Likely due to the fact they examined the fabrics on a cylinder tube and not a human body. In line with this, Mollendorf et al. (2004) suggest that increasing the friction resistance on the top half of the body can trip the boundary layer allowing the laminar flow to remain in a transitional state from the shoulders down, causing the flow to remain attached to the rest of the body, rather than transition early to turbulent flow. The rise in surface resistance was actually found in turn to overall significantly reduce pressure and wave resistance. Building on this, Rogowski, et al. (2006) discovered that a combination of a hydrophobic surface, high body coverage and the anisotropy related to the application of a water-resistant coating minimised friction resistance during passive drag. They established that simply a water repellent surface in isolation without the combination of the other noted factors, does not significantly reduce hydrodynamic resistance.

Therefore, in the context of this study, it has been recognised that surface characteristics of the swimming material are directly related to friction resistance and when developing material for competitive swimming, these factors should inform the basis for development. Yet, pressure and wave resistance are particularly relevant during the active drag phases of swimming and must be considered before a conclusion of drag reducing material factors can be devised. These factors, combined with knowledge of the enhanced mechanical properties of auxetic materials will inform the potential for auxetic material development and testing for this study.

2.7.2. Pressure and Wave Resistance

Pressure drag is determined as the difference in pressure between the front of the swimming body and the tail end (Naemi et al. 2010). Wave making resistance on the other hand is calculated as the energy lost due to the production of waves by the swimmer, which means less energy has been spent on forward propulsion and as a result causes resistance (Geer et al. 2012).

Many academics that have assessed swimsuit performance consider pressure drag to be the most dominant force out of surface friction, wave resistance and pressure drag, therefore a pressure drag reduction can be most beneficial to the swimmer (Pendergast et al. 2006; Bixler et al. 2007; Moria et al. 2010; Geer et al. 2012). Moria et al. (2010) estimate it to constitute of just below 90% of total drag. However, other academics from the field of biomechanics tend to disagree. Instead, they make the assertion that once the swimmer is at or close to the surface (water-air interface) above 0.5m and at a swimming speed of 1m/s-1 or above, wave-making resistance and pressure drag are combined the most significant forces, with wave drag actually dominating around 50-60% of total drag Vennell et al. (2006). The percentage split in these circumstances is dependent upon human ability, body shape and other various factors, but in general it is considered to be as follows; wave drag 59%, pressure drag 33% and skin friction 8% (Webb et al. 2011). Furthermore, it is possible that the contrast in views is due to many of the papers that investigate the hydrodynamic resistance features of swimsuits and swimsuit materials largely focus on passive drag at gliding depths, in order to exclude the influence of human ability, as discussed earlier. Therefore examining passive drag represents a situation where wave drag is negligible, thus contributing to a very little of the percentage split between the three drag types. Taking this into account, suggesting pressure drag as the dominating drag force may be inaccurate and misleading as there is evidence to suggest that it is below certain gliding depths but once the swimmer is close to or at the water air interface, wave drag tends to dominate. This is when active drag is experienced, which constitutes the majority of the swimming race. However, Bixler et al. (2007) found pressure drag to dominate during the glide phrase (60-70%) and academics such as Webb et al. (2011) consider that it typically represents 33% of the total drag force during active swimming. Therefore, over the whole race (glide phase plus active swimming) it can be assumed that reducing pressure drag should still be a major consideration when developing competitive swimming textile.

The human body creates pressure resistance due to raised body parts interrupting water flow, such as: 'the head, shoulders, buttocks, knee and heels' (Wu, 2011:236). Other swimming sea mammals on the other hand, have bodies that are contoured and designed specifically to be hydrodynamic when swimming, for example a dolphin. Wu (2011) concluded that theoretically, compression of these certain body zones, where applicable, should reduce hydrodynamic resistance. In the case of other contoured swimming sea mammals, the flow remains attached to the swimming body in laminar currents until it eventually separates towards to the end of the body, transitioning to turbulent. The late transition to turbulent allows them to remain hydrodynamic. Whereas due to the shape of the human body, the flow transitions much earlier in comparison from laminar to turbulent and remains turbulent along most of the body, thus increasing the hydrodynamic resistance (Naemi et al. 2010; Wu, 2011). Therefore, in relation to this study's investigation into factors that affect swimming, it is evident that if a swimsuit can contour the body to reduce pressure drag and delay flow transition, hydrodynamic resistance will be reduced.

Using computational fluid dynamic techniques (CFD) Marinho et al. (2012), examined the passive drag reducing effect of a full body Polyurethane swimsuit, a conventional textile suit and 'light underwear' (bikini style combination). Both the full body suit and conventional suit reduced drag, decreasing in magnitude respectively in comparison to the bikini style, they concluded that this was most likely due to the accurate compression of the specific body areas covered by the two suits. Although computational fluid dynamics cannot assess the reduction of 'wobbling masses', Marinho et al. (2012) were able to make this assumption because despite difference in body coverage, the contrast in friction drag values between the full body and conventional suits was small, in comparison to the difference in pressure drag between the two suits which was much more significant. The full body suit additionally covered the legs along with the torso, therefore more body coverage, resulting in more bodily compression can significantly reduce pressure drag, which is in line with the prediction of Wu (2011). However, it must be taken into consideration that only one female participant was used and the research was not conducted on a large scale. On the other hand, Geer et al. (2012) came to similar conclusions with a slightly wider participant base. By examining six swimmers and using 3D scanning analysis, they were able to convincingly support that compression to deform (streamline) the body by the swimsuit material can reduce pressure resistance.

It is also considered that compressing the muscles during swimming can not only create a better-streamlined shape for the athlete but also improve muscle power through a reduction in muscle and skin vibrations Wu (2011). In line with the literature studied, reviewing the 2015 triathlon collection from Speedo International found that double-layered fabric is 'strategically' placed to enhance performance and improve body positioning (Speedo, 2015). Conventional materials become thinner when extended due to their positive poisson's ratio and it is evident that to overcome this, brands such as Speedo incorporate double layers of fabric in areas of the body needing the most compression. Further investigations in the form of primary research is aimed at mapping were these areas may be. At this point, it is hypothesised that auxetic foams, due to their synclastic curvature would adhere to body contours more affectively and maintain maximum compression without the need for double layers as their structure expands under elongation.

A wide literature search returned limited research on the relationship between wave drag and a competitive swimsuit, most likely because active drag is more complicated to measure and examine due to the influence of human swimming ability. Despite this, the information that is available strongly supports how the correct material and fit of a swimsuit can positively influence swimming performance. As wave drag is directly correspondent to the swimmer's posture, researchers have found that increasing the body length by elongating the arms forward can reduce wave drag as well as deforming the body into a more hydrodynamic shape using compression to reduce waves that occur behind the body (Vorontsov et al. 2000 in Naemi et al. 2010; Geer et al. 2012). However as the extent of the relationship ratio between wave drag and swimsuit body deformation at the time of writing this research was not represented in academic literature. It is therefore assumed for the purpose of this study that the relevant parameters for reducing pressure drag through wearing a competitive swimsuit will subsequently assist in reducing wave drag.

Table 2.5 illustrates the combination of drag reducing properties and the academic sources that have tested and documented related theories. Now that the material factors of a swimsuit that can reduce wave, pressure and skin resistance have been acknowledged, with these in mind, auxetic materials are explored for their potential to enhance swimming performance.

Source	Table. 2.5 Hydrodynamic Reducing Factors					
	Bodily compression factors that reduce pressure and wave resistance		Material surface factors that reduce friction drag			
	Compression into hydrodynamic shape	Compression to reduce muscle oscillation	General links to material surface and friction resistance	Macro-scale smooth surface	Micro-scale surface roughness	Water repellent chemical surface finishing
Geer et al. (2012)	X					
(Wu, 2011).	X	X				
Marinho et al. (2012	X					
Mollendorf et al. (2004	X					
Abasi et al. 2013				X		
Buder and Odenwald (2010)			X			
Cortesi et al. (2014	X		X			
Moria et al. (2011)					X	
Rogowski, et al. (2006)					X	X

2. 8. Potential Application of Auxetic Foams in Wetsuits

Traditional wetsuits for outdoor swimming are neoprene based. Table 2.6 identifies the fabric properties of outdoor swimming wetsuits marketed by two sports brands, 2XU and Orca and links the material properties highlighted within literature (and presented in table 2.5) that are considered to improve swimming performance. It has already been established by consulting literature that bodily compression can lead to pressure and wave drag reduction, along with a smooth fabric surface leading to skin friction reduction (Mollendorf et al. 2004; Rogowski et al. 2006; and Moria et al. 2011; Wu, 2011; Geer et al. 2012; Marinho et al. 2012; Abasi et al. 2013). Table 2.6 demonstrates how wetsuit brands and manufacturers market their products in accordance with this research but also include other factors that can improve performance by encouraging freedom of movement and comfort.

Table 2.6 Considerations When Developing Competitive Wetsuits - Material Factors

Brand	Suit	Material factors that are found in literature		Other material factors specified by brands	
		Compression to reduce pressure, wave drag reduction and reduce muscle oscillation	Smooth fabric to reduce Skin friction reduction	Comfort	Freedom of movement
2XU (SigmaSport, 2016)	V3 Velocity wetsuit 2015	Compression for optimum performance.	'Zone Stretch Panels' (ZSP) to enhance fluid movement over the wetsuit surface.	Seamless shoulder and arm panel reduces arm fatigue.	Use of stretch material enables improved lateral flexibility as well as being non-restrictive.
Orca (Orca, 2016)	RS1 Predator	'Pressure function neoprene' to provide active compression.	'Nano-ice' coating - a 'fast' material coating.	'Bamboo infinity skin lining' and special grade neoprene provides comfort.	'Bamboo infinity skin lining' and special grade stretch neoprene enhances flexibility.

2.8.1. Areas where Auxetic Materials Can Add Value to Competitive Swimming

The next two sections discuss the potential of auxetic foams for competitive wetsuit applications. The predictions made in this section inform the creation of the research hypotheses. The predictions of the potential characteristics of auxetic foam for competitive swimming are split into the four material categories derived from table 2.6, 1) bodily compression to reduce pressure and wave drag, 2) providing a smooth surface to reduce skin friction, 3) freedom of movement and 4) wearer comfort.

2.8.2. Bodily Compression to Reduce Pressure and Wave Drag

As discussed earlier, one of the unique characteristics of auxetic materials is their ability to expand when under tension and harbour a synclastic curvature, due to their negative Poisson's ratio (Alderson and Alderson, 2007). As a result of these characteristics and in the context of this study, auxetic foams are predicted to enhance the compression features of a competitive swimsuit. Particular areas which require compression in order to streamline the body have been identified as the legs, torso and buttocks (Wu, 2011; Marinho et al. 2012). It is anticipated that as conventional materials become thinner under tension in a compressive garment, their functionality reduces. Auxetic materials on the other hand are predicted in these conditions to provide enhanced stability as they expand when under tension.

2.8.3. Freedom of Movement, Wearer Comfort and a Hydrodynamic Surface

When researching auxetic materials for sports applications, Sanami et al. (2014) found that the auxetic foam was more resistant under uniaxial compression than the conventional foam. It is predicted that due to the propulsive actions that a human body makes during swimming, a competitive swim garment would be repeatedly subject to uniaxial compression, for example around the hip joint during breast stroke. As auxetic foam is found to be resistant to compression, in a wetsuit situation, it is hypothesised that auxetic foam could provide stability around these areas rather than creasing or bulking as a traditional foam or material would. In theory, this in turn could lead to a reduction in hydrodynamic resistance as it was identified earlier that that on a macro level, a smooth surface with minimal surface creasing will reduce the level of hydrodynamic resistance of an athlete whilst swimming (Abasi et al. 2013). The ability of auxetic foams to contract under compression and expand under tension may also increase flexibility around joint areas, allowing greater freedom of movement but also increasing comfort levels due to a reduction in pressure around these areas. This study did not find evidence of auxetic foams being assessed for their NPR response over complicated and contoured shapes, such as the human body and therefore as the potential benefits of auxetic materials to wetsuits are concerned with an auxetic response over complicated shapes, primary research methods will aim to explore this area.

2. 9. Chapter Summary and Research Hypotheses

Auxetic materials are considered to be an interesting class of materials with extraordinary characteristics and behaviours. Researchers have identified many industries where auxetic materials have enhanced application potential, such as; personal protective clothing, geotextiles, filtration systems, aerospace, performance sportswear, automotive, medical textiles (Ugbolue et al. 2010; Alderson et al. 2012; Critchley et al. 2013a). This summary presents an opportunity to identify the key hypotheses of this research that will be examined further through primary research. The literature scrutinised supports the suitability and potential of utilising auxetic materials in competitive sportswear applications but has also highlighted that there is a lack of documentation of their real-time use in sport utilisation (Wang and Hu, 2014). Therefore, the next stage of this research, which employs primary research methods, will attempt to investigate further their potential in two areas of competitive aquatic sports; wetsuits for professional swimming and impact protection vests used in watersports such as kitesurfing and windsurfing.

Swimming hydrodynamics were explored in order to gain a greater understanding of how auxetic materials may enhance functional swimwear. Two hydrodynamic drag reducing material factors were identified, 1) specific bodily compression elements and 2) friction minimising surface characteristics. By studying the latest developments in competitive wetsuit swimwear on the commercial market, additional material features such as 3) comfort and 4) freedom of movement were acknowledged as performance enhancing (Mollendorf et al. 2004; Rogowski et al. 2006; Moria et al. 2011; Wu, 2011; Geer et al. 2012; Abasi et al. 2013;

Sigmasport ,2015; Orca, 2015.) All four characteristics provide a basis for exploring the potential for auxetic materials to enhance these features. Similarly, when researching the purpose of impact protection vests, three main characteristics were highlighted, 1) freedom of movement 2) impact protection and 3) lightweight material (Abersochwatersports 2016; O'Neill, 2016). The primary research will therefore focus on examining the auxetic foam in the context of these properties.

Auxetic textiles and foams were both explored, however auxetic textiles were not considered at the time of writing this study as advanced enough to pursue as a development for compression garments in the context of this research. This was mainly due to the most progressive auxetic textile samples in this research area, reverting to positive Poisson's ratio at high strains and also being complicated to manufacture (Hu et al. 2011; Ugbolue et al. 2011; Alderson et al. 2012). Therefore, auxetic foam manufacturing techniques were explored further and the information gathered informed the development of a unique thermo-mechanical conversion process for this study. Nevertheless, a comprehensive investigation was undertaken into the potential of auxetic textiles for competitive swimwear application and should inform any future research in this area. It is also anticipated that the laboratory testing designed to examine the behaviour of auxetic foam in competitive wetsuits will provide a grounding of knowledge indicating the potential of auxetic textiles in competitive swimwear.

For the purposes of conducting primary research, a set of research hypotheses have been drawn from the literature review;

Hypothesis 1*:* New auxetic foams can be developed from manufacturing techniques adapted from existing methods. (Auxetic foams can be engineered to suit real-world situations).

Auxetic foam manufacturing methods and mechanical behaviours have been a focus of this literature review and the information gathered should aid the adaptation of the traditional thermo-mechanical method, first discovered by Lakes, for the primary research in the form of the first hypothesis of this study. This research will undertake an adaptation of the thermo-mechanical conversion process similar to that employed by Sanami et al. (2014) and Allen et al. (2015b). The method is discussed in detail in the methodology chapter.

Hypothesis 2: Auxetic foams provide enhanced resistance to impact in watersport protection vests.

The evidence to support the use of NPR foams in applications where indentation or impact resilience is vital is very promising. To date, many academics have proven, albeit on a small experimental scale, that auxetic foams could replace their conventional counterparts in many industries (Alderson and Alderson, 2007; Darja et al. 2013). However, currently, there are few developments dedicated to the advancement of auxetic foams for sport specific applications. The research by Sanami et al. (2014) does support the concept of utilising auxetic foams in sport, but the recommendations are centred toward sporting apparatus such as cricket bats, batting gloves and shin pads. This research on the other hand will continue to further explore how auxetic foams, may be suited to being worn on the body to enhance impact protection in water sport vests.

Hypothesis 3*:* Auxetic foams enhance compression zones in competitive swimming wetsuits. Initial recommendations can be made as to where these 'zones' should sit in a garment.

The literature scrutinised has revealed a set of unique characteristics of auxetic materials that, in the context of this study, have the potential to enhance swimming performance and will be investigated further using primary research methods. Primary research will also aim to make initial recommendations on where in a garment auxetic foams would be best placed. Auxetic materials are known to exhibit a synclastic curvature (Alderson and Alderson, 2007). Due to this behaviour and in the context of this study, it is predicted that auxetic foams will conform to the body contours more effectively, thus enhancing compression. It was found that competitive swimming garments are designed to compress the athlete's body in order to reduce hydrodynamic drag (Wu, 2011; Geer et al. 2012). However, as conventional materials become thinner when under uniaxial tension, it is assumed that their ability to provide stable compression is weakened due to the thinning of the fabric in highly compressive areas. On the other hand, auxetic materials behave in the opposite way and expand when under tension (Chan and Evans, 1998; Darja et al. 2013; Wang and Hu, 2014). Used in highly compressive wetsuit, it is predicted that auxetic foams may maintain compression and stability and prevent over-extension of the fabric, in comparison to conventional materials, thus providing enhanced compression zones.

Hypothesis 4*:* Auxetic foams improve comfort and freedom of movement for watersport protection vests and competitive swimming wetsuits. Initial recommendations can be made to advise where these areas sit in a garment.

As auxetic materials contract when compressed (Chan and Evans, 1998; Darja et al. 2013; Wang and Hu, 2014), it is predicted that in places where a conventional neoprene based suit would crease during swimming due to movement, for example around hip joint, auxetic foam should remain smooth, reducing surface creasing. This in turn could reduce the hydrodynamic resistance of the athlete and increase freedom of movement in these areas. Competitive Swimsuit brands have highlighted comfort as a key feature of their swimsuits and the ability of auxetic materials to contract when compressed and expand when under tension could potentially relieve pressure and restriction of movement at joints. Water sport protection vests also require a high level of function for their application, protective materials that also allow the athlete maximum freedom of movement (Abersochwatersports 2016; O'Neil 2016; Body Glove, 2016). Again, auxetic foams have the potential to improve these aspects and will be assessed in line with these predictions. Primary research will also aim to inform initial proposals as to where in wetsuits and impact vests, auxetic foams should be situated.

The four hypotheses will be further evaluated using primary research methods, outlined in the methodology chapter. The results from the primary research, combined with the knowledge gained from secondary research should ultimately lead to proving, disproving or building on each hypothesis. The extent to which this is achieved will be discussed in chapter 4, Results and Discussion.

Chapter 3. Methodology

This chapter brings together the various research methods under the hypothetic-deductive method that are adopted for this study and critically appraises each method in order to validate the results. This chapter links each of the study objectives to the related research method used to achieve the objective, whether it is primary, secondary or a mixture of both. Finally, a focus on the primary research methods is included which outlines laboratory test methods and provides justification for the use of each procedure. It is important to acknowledge that the inherent limitation in the manual approaches to laboratory testing enabled a limited amount of specimens to be tested.

3. 1. Aim One and Aim Two

A review of literature was conducted in order to establish a broad understanding of auxetic materials and in related applications and to achieve aim one of the research study. In accordance with aim one, to establish the potential, performance and behaviour of auxetic materials for competitive aquatic sport applications, relevant academic literature was critically appraised. The research considered the origins of auxetic materials, explored different forms of auxetic materials such as foams and textiles, their mechanical behaviours and manufacturing techniques and appraised the current stage of development as novel materials. This grounding of information enabled adequate primary research methods to be decided upon to further explore and achieve aim one. To achieve the second aim, literature was reviewed in order to determine the contextual factors that influence the performance of athletes in competitive aquatic sports. The literature review covered subjects such as; the fluid mechanics of human swimming and investigating the properties of swimsuit materials that can reduce hydrodynamic resistance and the functions of a watersport impact protection vest. Overall, the literature review conducted in the context of aim one and aim two provided the theory on which the hypotheses were formed to be subsequently examined through primary research in aim three.

3. 2. Aim Three

Completion of aim three was achieved through primary research. The primary examination research methods were determined once the relevant literature had been appraised in line with aims one and two. The hypotheses that were examined in accordance with aim three, to develop auxetic foams and assess their suitability, behaviour and potential in competitive swimming wetsuits and watersport impact protection vests, were drawn from the conclusions of aims one and two. The test methods were designed to prove, disprove or build upon each hypothesis and overall, the results allow the potential behaviour of auxetic materials in competitive swimwear and watersport protection to be predicted.

3. 3. Research Hypotheses

Hypothesis One: New auxetic foams can be developed from manufacturing techniques adapted from existing methods. (Auxetic foams can be engineered to suit real-world situations).

Hypothesis Two: Auxetic foams provide enhanced resistance to impact in watersport protection vests.

Hypothesis Three*:* Auxetic foams enhance compression zones in competitive swimming wetsuits. Initial recommendations can be made as to where these 'zones' should sit in a garment.

Hypothesis Four: Auxetic foams improve comfort and freedom of movement for watersport protection vests and competitive swimming wetsuits. Initial recommendations can be made to advise where these areas sit in a garment.

3. 4. Primary research Methods

The following section critically appraises each of the individual primary research methods. These include a conversion process to manufacture auxetic foams, test methods performed on auxetic foam samples and observational assessment methods carried out on a competition triathlon wetsuit made from conventional materials.

3.4.1. Auxetic Foam Development and Testing

In order to convert the conventional foam to auxetic, a conversion process needed to be outlined. The foam development and testing section of this research paper was conducted as follows. The conventional foam was converted into auxetic foam utilising a method based upon a thermo-mechanical method. This will be explained in further detail in Chapter 3 Methodology. Once the foam has undergone the conversion process, the next stage was to examine the mechanical properties of the auxetic foam in comparison to the conventional foam. Conducting these tests allows the Poisson's ratio of converted foam to be examined, thus confirming whether or not the conversion process was successful in producing an auxetic foam. The next stage in the development process examined the auxetic samples for their suitability to be used within a competitive swimming garment and impact protection watersport vests using laboratory test methods and create initial recommendations on where these areas of each garment may be. The test methods are covered in detail in the Methodology chapter 3.

3.4.2. Auxetic Foam Conversion Method

Methods to convert conventional foam to auxetic using the thermo-mechanical process founded by Lakes in the late 1970's have already been discussed in the literature review section of this research. However, it is well reported within literature that development parameters such as; compression ratio, oven temperature and time are directly influenced by the conventional foam material specifications such as; open or closed cell, pore size, density and material specifications (Critchley et al. 2013a). This thesis will follow a similar conversion process conducted by Sanami et al. (2014) and Allen et al. (2015b) as their manufacturing method features a conventional foam of similar specifications. The foam used for this study was purchased from an online retailer (www.aquariumonline.co.uk). It was a reticulated polyurethane foam with 30 pores per inch (ppi).

Step One: Volumetric Compression

The compression ratio is the difference between the volume of the conventional foam and the auxetic foam after conversion. As discussed in the literature review, researchers consider compressing the conventional foam to between 50% and 80% of its original size to yield the most successful conversion results (Critchley et al. 2013a). Allen et al. (2015b) use a linear compression ratio of 0.7 in each of the three planes and so this research used a method to compress the foam to 70% of its original length in order to buckle the cell ribs sufficiently and create the auxetic sample.

Step Two: Heating and Annealing

When following the thermo-mechanical conversion process, the conventional foam sample should be subjected to a prescribed heat for a specified time in three stages whilst under compression (Critchley et al. 2013a; Sanami et al. 2014; Allen et al. 2015). Following similar heating and annealing stages documented by Allen et al. (2015b), the mould with the compressed foam sample was placed in the oven at 180°C for 25 minutes. The sample was removed, stretched by hand gently and placed back into the mould and into the oven. The first step was then repeated. Once the foam had been removed from the mould and gently stretched a second time, it was then placed back into the mould and into the oven for a further 20 minutes but at a lower temperate of 100°C. This is called the annealing stage. Allen et al. (2015b) used slightly different variations on time and heating temperature. For example their sample was heated at 180^{c} twice for 30 minutes and 100^{c} for 30 minutes. As the sample used in this study is of smaller dimensions, the conversion process has been adjusted accordingly. Table 3.1 documents the three heating stages of the conversion process.

Table 3.1 Thermo-mechanical Heating Stages

First heating stage	180°c for 25 minutes followed by stretching
Second heating stage	180°c for 25 minutes followed by stretching
Annealing stage	100°c for 20 minutes

3.4.3. Compression Mould Dimensions and Compression Ratio

In order for the thermo-mechanical conversion process to be achieved in-house, a compression mould needed to be constructed. The mould design was similar to that used by Allen et al. (2015b). The mould was constructed in aluminum with the inner dimensions being 100mm x 100mm x 35 mm. The conventional starting foam had dimensions of 143mm x 143mm x 50mm, therefore smaller mould dimensions exhibit the desired linear compression ratio of 0.7 in all three planes over the foam. The aluminum mould is pictured in figure 3.1.

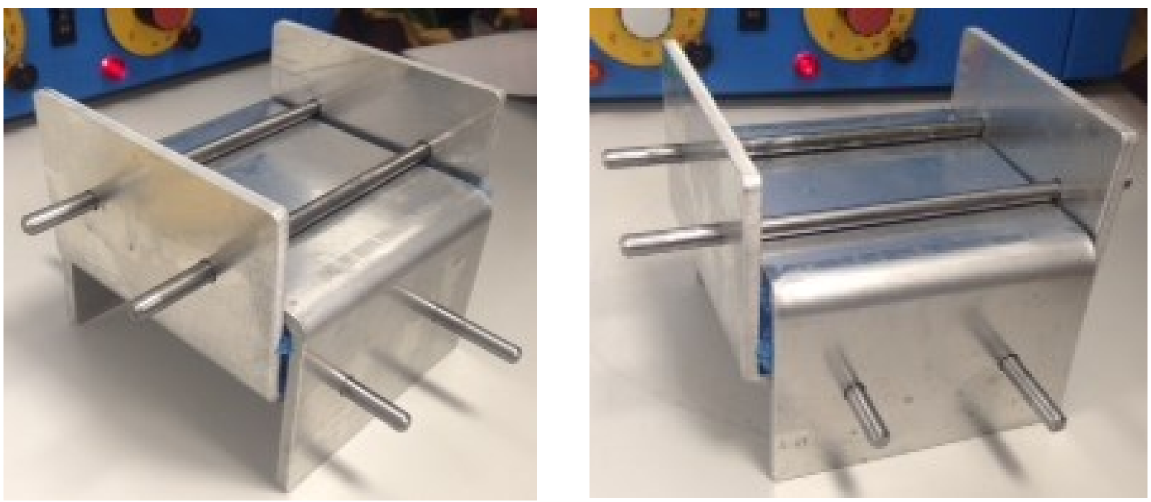


Figure 3.1 Aluminium mould

3.4.4. Foam Testing

This research is concerned with examining the material properties of auxetic foams and so the test methods chosen or created were deemed most suitable to examine their properties in relation to competitive swimming wetsuit and water sport protection vest applications.

3.4.5. Foam Preparation for Testing

Once the foam had undergone the conversion process, the dimensions of the foam straight from the compression mould were approximately 100mm x 100mm x 35mm. The measurements are an approximation due to surface creasing, the impact of this is discussed further in the Results and Discussion Chapter 4. From the converted foam block, smaller blocks measuring between 8mm thickness and 33mm were cut specifically for testing. All of the test specimens were tested in a conditioned testing laboratory, maintained at 25 ± 5^{o}C and 65% relative humidity. For the purpose of this research, it was necessary to analyse the auxetic and conventional foam at different thickness levels to gain an understanding of the auxetic behaviour in different situations. For example, ideally, the foam used within a competitive wetsuit would be thinner than the initial converted dimensions. Therefore in order assess thinner samples, the foams had to be sliced, a freehand razor blade was used to do this.

3.4.6. Microscopic Cell Imaging

A digital microscope (Dinolite AM400/ AD4000 series) was used to take microscopic images of the unconverted and converted cell structures. This method was chosen in order to compare the converted foam to other authors such as Allen et al. (2015b) who have included microscopic images within their studies in order to display the different cell geometry post conversion.

3.4.7. Poisson's Ratio

Testing for Poisson's ratio determines whether the foam that has undergone the conversion process is auxetic or not. In order to determine the Poisson's ratio value, the engineering strain must be calculated. The engineering strain value can be gathered through applying strain to the sample either through an extension test or a compression test method. Both test methods were used as primary research methods for this study. It is predicted that the Engineering stress-strain relationship will change once the conventional foam is converted into auxetic foam. The equations for stress and strain will be used to evaluate the foams in relation to Poisson's ratio. The relevant equations can be seen below. Poisson's ratio was calculated using equation (2).

The equations for Poisson's ratio (v) can be expressed as;

$$v = -\frac{\varepsilon\ transverse}{\varepsilon\ longitudinal} \tag{2}$$

Where strain is denoted by the symbol ε.

Engineering Strain (ε) can be expressed as;

$$\varepsilon = \frac{\Delta l}{l} \tag{3}$$

Where, Δl is change in length (cm) and l is initial length (cm).

Engineering Stress can be expressed as:

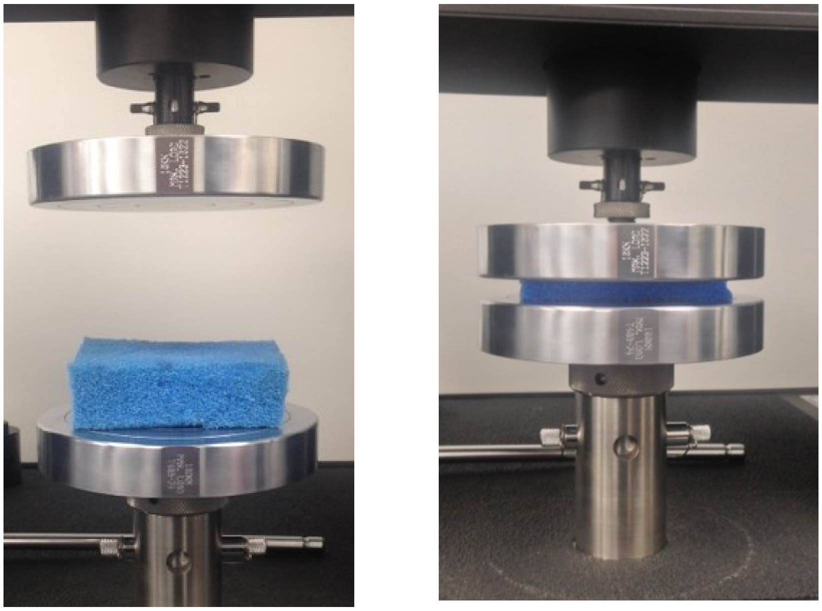
$$\sigma = \frac{F}{A} \tag{4}$$

Where, *F* is Force and *A* is Area.

3.4.8. Compression Test Method

The method adapted for this research was based upon other similar methods used by researchers in this area such as Allen et al. (2015b). An Instron machine (Series 4460) used for this test method fitted 5kN load cell and is a universal testing machine that has the flexibility to be used as Constant Rate of Traverse (CRT) and Constant Rate of Extension (CRE).

The foam specimen was placed between the test plates by hand and adjusted to ensure it was sitting accurately in the middle of the plates (figure 3.2a). The top plate was manually lowered using the jog control to apply compressive load to the sample and paused at specific intervals, figure 3.2b shows compressed foam sample. Whilst the plates were paused, a reading of the Kilogram force (kgf) was recorded, along with the new, changed dimensions in both the longitudinal and transverse directions. The original length and subsequent changes in length in both directions were then used to calculate strain and Poisson's ratio using the Strain and Poisson's ratio formulas. An illustration of the test method. The force (Kgf) and change in cross sectional area of the test specimens was also used to calculate the engineering strain. Stress-strain and transverse strain-longitudinal strain relationships were then evaluated.



(a). Sample on compression plates (100mm x 100mm x 30mm)

(b). Sample compressed to 70% (100mm x 100mm x 30mm)

Figure 3.2 Diagrams of compression testing

3.4.9. Foam Density Testing

The density (p) of conventional and converted foams for this study were calculated using the below equation. The density was obtained from conventional and converted specimens in order to calculate the density change as a result of the conversion process.

$$p = \frac{M}{V} \quad (5)$$

Where, M is mass and V is volume.

3.4.10. Impact Attenuation Test Method

As this study is concerned with examining the potential of auxetic foams to improve resistance to impact in watersport protection vests, an impact attenuation method was determined suitable to examine this behaviour.

The IRB hammer and anvil test was considered the most appropriate test method to examine the impact attenuation properties of auxetic foams. The test prescribed by the International Rugby Board examines the impact attenuation of shoulder pad material, which involves the protective material being struck with a predetermined weight. The peak force was recorded in kilonewtons (kN) and the duration of impact recorded in milliseconds (ms). The results of this test provide an insight into the effectiveness of the material's ability to reduce the impact experienced by the wearer. Different impact velocities can be created by varying the mass of the impactor and the drop height (Pain et al. 2008; Tyler and Venkatraman, 2012).

An impact velocity of 1.5J and 5J were examined. These measurements were deemed most suitable to replicate the impact experienced by the material in a watersport impact protection vest, table 4.1 lists details of the four different tests that were conducted on both auxetic and conventional foams. For the purpose of this research, it was essential to examine the foam both under low and high impacts to quantify the auxetic behaviour in both instances. The impact velocities used provided preliminary results and more accurate testing can be conducted for further research once the initial examination of auxetic foam has been conducted in this instance. The impactor shape highly influences the consistency of impact experienced by the testing sample. Other variations of this test method use rods or more complicated shapes but for the purposes of this research, both impactors used were spherical. The adaptation to use a spherical shape allowed the consistent shape of the sphere to yield results that were easily reproducible and also comparable. As the purpose of this research is to compare conventional and auxetic foams, testing conditions needed to be reproducible and reliable in order to make accurate and valid comparisons. A square shape for example could strike the sample at a slightly different angle each time which can lead to variable impact results, which for this type of research in undesirable (Tyler and Venkatraman, 2012).

Table 3.2 Impact Attenuation Tests			
Test Name	Impact	Specimen thickness	Test Description
Test One	5 Joule	50mm (conventional) and 35mm (auxetic)	Original foam (50mm thick) compared to converted foam (35mm thick).
Test Two	5 Joule	33mm	Comparison of auxetic and conventional foam 33mm thickness under 5j impact test.
Test Three	1.5 Joule	15mm	Comparison of auxetic and conventional foam 15mm thickness under 1.5j impact test.
Test Four	1.5 Joule	8mm	Comparison of auxetic and conventional foam 8mm thickness under 1.5j impact test.

The test equipment was custom made by INSPEC UK, an external testing house. Figure 3.3 illustrates the impact attenuation test method apparatus. The test sample was placed by hand between the centre markings on the sacrificial or anvil plate, without being fixed into place. The 'hammer' or impactor, was dropped from a prescribed height, which impacted the test sample. The anvil plate captured the impact peak force and impact duration through sensors and the information was recorded on the connected computer database **(**Tyler and Venkatraman, 2012). Each sample was tested five times in order to ensure that the results were repeatable and therefore reliable.

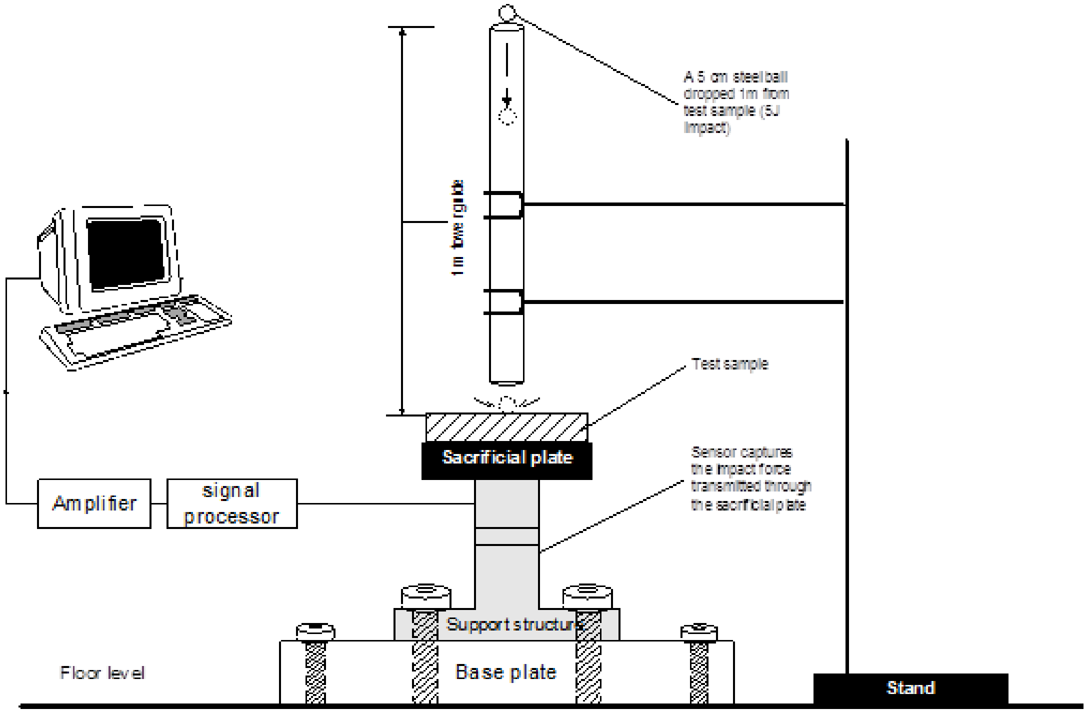


Figure 3.3 Impact Attenuation Testing Apparatus (Tyler and Venkatraman, 2012)

3.4.11. Flexural Rigidity and Bending Length Test Method

In order to determine the potential of auxetic foam in a compressive wetsuit for competitive swimming, a test needed to be adapted that examined auxetic behaviour in contoured positions. The test method used in this study is an adaptation of the British Standards (BS 3356:1990) method for determination of bending length and flexural rigidity. Although the test method is primarily designed for examining textiles, it was deemed appropriate for this research, as the foam developed for this work will be worn on the body, rather than in a separate piece of sporting apparatus. As the potential type of garment that the auxetic foam will be used within is a compressive, tight fitting garment, examining the flexural rigidity of the auxetic foam will indicate whether it has the potential to conform to body contours. A fabric with a low numeric value for bending length will achieve a low flexural rigidity measurement and therefore conform to the body better than that which achieves a high value.

This test method used Shirley Stiffness Tester apparatus in order to obtain bending length. The test method is structured as follows. The specimen was cut to the desired dimensions using a template and placed on the testing platform. The specimen was then gently guided over the platform by hand, with the bending measurement ruler placed on top of the sample and the sample began to 'droop' over the edge of the platform. A measurement was taken in centimetres (cm) once the sample had reached the bending guidelines. This test was repeated three times in line with industry standard according to the BSI test method. This enabled a reliable result to be obtained and to prove that the test is repeatable and therefore a valid way to examine material behaviour. Flexural rigidity is expressed using formula (6).

$$G = M \times C^3 \times 9.087 \times 10^6 \, \mu Nm \qquad (6)$$

Where, G is Flexural Rigidity, M is mass per unit area (gm^2) and C is bending length (mm).

3.4.12. Wetsuit Material Assessment

A conventional neoprene Speedo wetsuit was assessed to inform where different functional materials are used within a conventional garment. The results will indicate where auxetic foam has the potential to be used in such a garment. An observation method was chosen for this section of the methodology so that the garment may be preserved and not destroyed in the process of testing the material. Observational methods were also deemed appropriate in the context of this research as the wetsuit material was not a focal point for testing at this stage, instead developing and testing the auxetic and conventional samples was the purpose of this study.

Firstly, information from the care label was noted and the material construction itself identified using a piece glass. By observation technique, different panels within the garment construction were identified. A thickness gauge apparatus was then used to examine the varying thickness levels of such panels. The information gained from these simple tests was then used to inform where auxetic panels may be appropriately placed within a similar garment.

3.4.13. Thickness Gauge

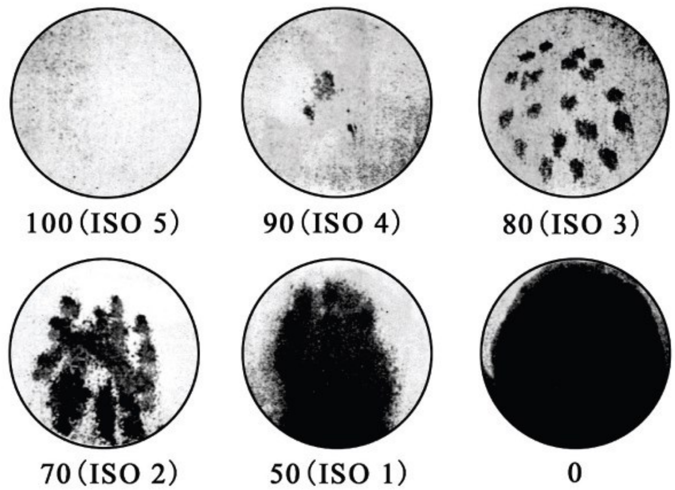
The equipment used to test the thickness of the material in the Speedo wetsuit was a Mitutoyo thickness gauge 7301 with a 0-10mm dial thickness gauge which has an accuracy of ± 5µm.

The material in question was placed between the 'jaws' of the thickness gauge and the jaws were released. The jaws closed either side of the material using a small amount of pressure which then generated a thickness measurement for the specimen. This test was repeated three times, in line with industry standards.

3.4.14. Water Repellency Testing

Testing the Speedo neoprene wetsuit for water repellency should give a strong indication how water repellent the material is. This test was used as the aim was to evaluate the wetsuit material surface characteristics and not the fabric itself, hence why a water immersion method to evaluate absorption was not explored for this study. The test method adapted for this study was based upon the British Standard (BS EN ISO 4920:2012). As the neoprene sample tested was still in a full suit, the material was not cut to testing specimen size and instead the suit itself, in a single layer was placed onto the apparatus. Five areas of the torso and back panels were examined and the results were recorded. It was assumed that the areas tested were a true representation of the other areas of the garment that could not be tested, for example the arm and leg panels.

A sample was placed on an embroidery loop and 250ml of distilled water was poured onto the sample from the funnel part of the testing apparatus. The reading was then recorded in accordance with the British Standard marking system, see figure 3.9.



100 no sticking or wetting of the specimen

90 slight random sticking or wetting of the specimen face

80 wetting of specimen face at spray points

70 partial wetting of the specimen face beyond the spray points

60 complete wetting of the entire specimen face beyond the spray points

0 complete wetting of the entire face of the specimen

Figure 3.4 British Standard water repellency marking guide

3. 5. Chapter summary

This chapter has identified the various primary and secondary test methods utilised within this study. An in-depth explanation of the primary test methods and the auxetic conversion process adapted for this study were conducted. The next chapter, 4 results and discussion, will conduct the laboratory development and testing and utilise results from both the primary and secondary research techniques, outlined within this chapter, to draw conclusions in line with the research objectives and hypotheses.

Chapter 4. Results and Discussion

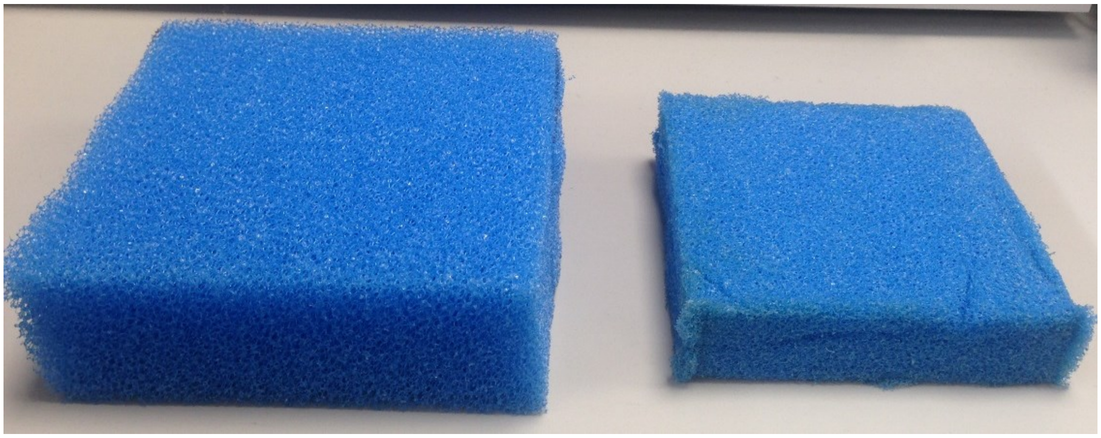
This chapter discusses the results obtained in this project that accomplished the research objectives by examining the research hypotheses. The results are discussed in relation to the study objectives and hypotheses made from conducting the literature review. The auxetic foams were evaluated for mechanical properties and to determine how auxetic foams can be embedded into aquatic sporting garments and how it affects athlete performance. Further comments are also made on the overall progress of research in this area.

4. 1. Auxetic Foam Conversion Results

Auxetic foams were successfully developed from conventional foam as part of the primary research of this study. The results of testing for Poisson's ratio value will be discussed in more detail later in this section. Their mechanical performance was then examined under laboratory conditions and the test results are presented and discussed.

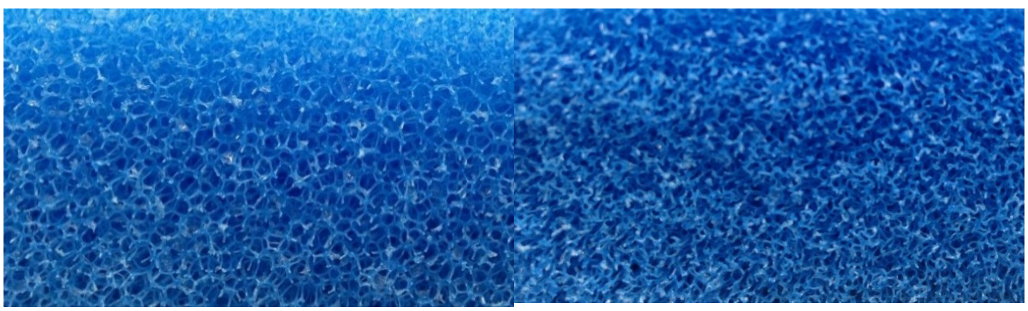
4.1.1. Converted Specimen

The thermo-mechanical process outlined in the Methodology chapter successfully converted conventional foams into auxetic using multiaxial compression in all three planes. A comparison of the conventional and converted foam blocks can be seen in figure 4.1. The foam density increased from 0.258 gm^3 to 5.018gm^3, which is nearly double and in line with previous studies (Sanami et al. 2014; Allen et al. 2015b). An increase in foam density is expected due to the conversion process. Essentially the foam sample is compressed to smaller dimensions but it still contains the same amount of cells, therefore the cell ribs buckle and the sample increases in density after conversion. (For full material specifications see appendix A.) A visual example of the foam cell structure before and after conversion can be seen in figure 4.2. The convex cell walls of the converted foam are characteristic of auxetic foam and similar to that seen by other researchers such as Allen et al. (2015b) Figure 2.1b, after using a similar conversion technique and same compression ratio (0.7 in all three planes).



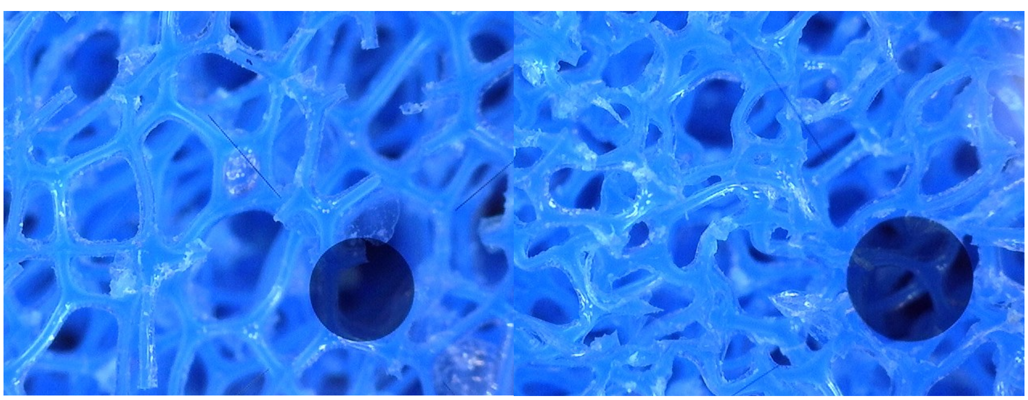
(a) conventional foam *(b) converted foam specimen*

Figure 4.1 Foam Specimens



(a) Foam cells before conversion (unconverted foam).

(b) Foam cells after conversion (auxetic foam).



(c) Foam cells before conversion, black dot indicates 1mm diameter (unconverted foam).

(d) Foam cells after conversion, black dot indicates 1.5mm diameter (auxetic foam).

Figure 4.2 Auxetic and conventional foam cells.

4. 2. Practical Limitations of the Conversion Process

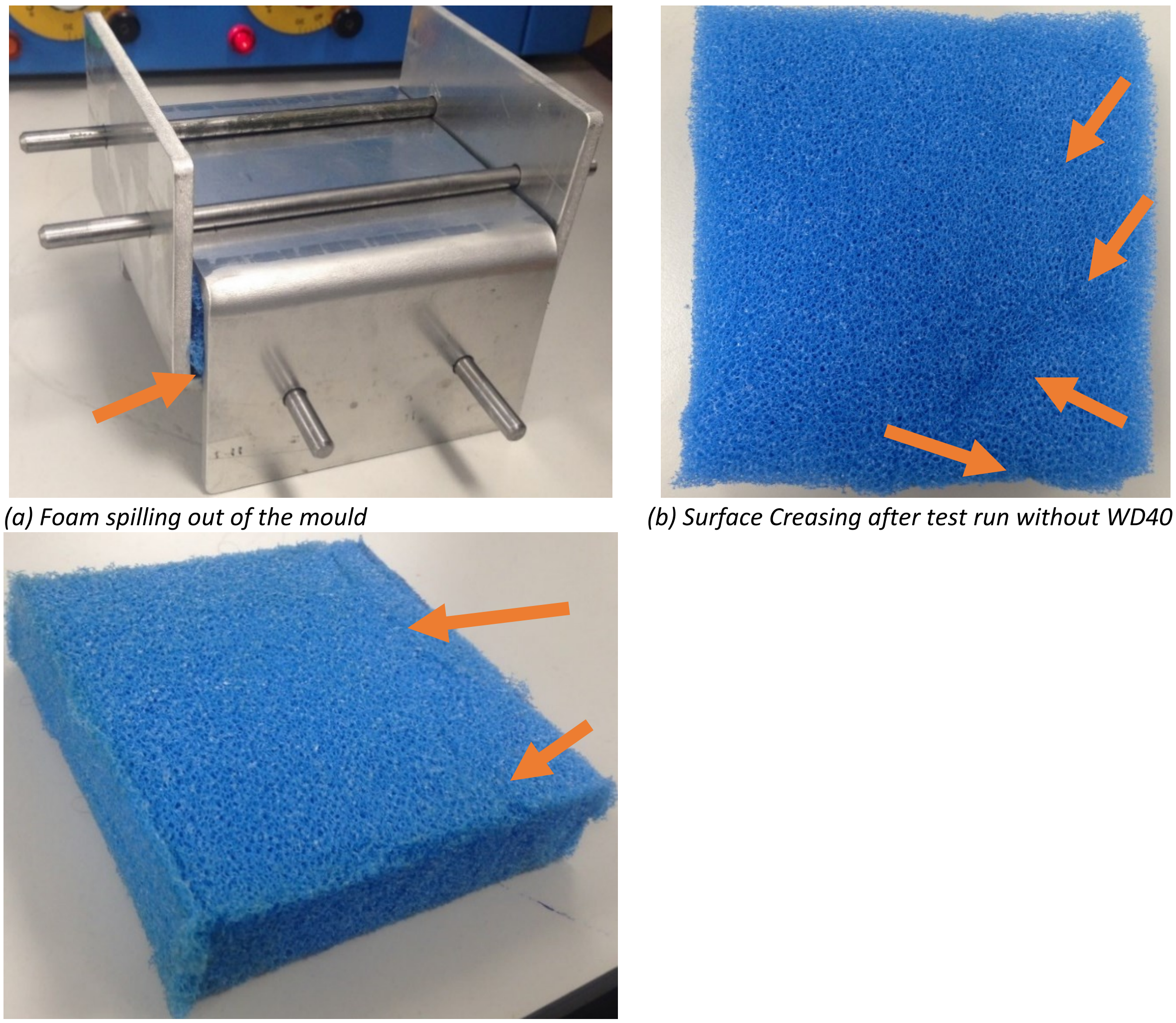
It has been well documented and discussed in this study that converting conventional foam to auxetic using the thermo-mechanical process can present some potential issues, such as creep and surface creasing (Chan and Evans, 1997). The auxetic foams produced in this study did not experience creep and revert to their original properties with a positive Poisson's ratio instead, they remained auxetic post conversion. However, surface creasing did occur and its implications to this study are discussed.

4.2.1. Surface Creasing

Foam creasing occurred after the foam was left in the mould for 20 minutes (without WD40) as a test run. The resultant foam specimen also had some surface creasing once converted. It was difficult to ensure that the foam was not spilling out of the ends of the mould once inserted, figure 4.3a. This indicated that the sample must have been creased inside of the mould. An example of the foam creasing on a converted and unconverted sample can be seen in figure 4.3b and 4.3c. However, it was determined that the addition of the lubricant (WD40), primarily to prevent to the foam from adhering to the mould walls, enabled the foam to adjust within the mould in such a way that reduced surface creasing.

Surface creasing on the auxetic samples resulted in the converted sample height dimensions being slightly uneven. For example, the first sample that was converted measured a varying height between 35mm and 30mm. Surface creasing is a common issue with thermo-mechanical conversion technique, as found by other researchers (Chan and Evans 1997a; Critchley et al 2013b; Duncan et al. 2016a). This means that the auxetic specimens were not homogenous, which is an issue that can affect the Poisson's ratio of the resultant foam. The lack of homogeneity of the auxetic foam produced as part of this research results in the auxetic properties being unreliable and future research should focus on developing ways to insert the foam into the mould with minimal creasing, thus producing more homogenous samples. For example by utilising novel methods found to reduce creasing such as, including rods in the compression mould (Duncan et al. 2016b).

Surface creasing leading to uneven samples also affected accuracy when slicing the converted foam samples into smaller specimens for testing. It is predicted that the stiffness of the foam, due to the modulus, used in this experiment increased the risk of surface creasing. A foam with a lower starting modulus and therefore much more flexibility may decrease the risk of surface creasing.



(a) Foam spilling out of the mould

(b) Surface Creasing after test run without WD40

(c) Surface creasing on a converted sample

Figure 4.3 Auxetic foam Surface creasing

4. 3. Poisson's Ratio Test Results

The conversion method used in this study successfully produced negative Poisson's ratio foam from conventional, reticulated open cell Polyurethane foam. Poisson's ratio for the converted foam was calculated using equation (2). Figure 4.5 presents longitudinal strain- lateral strain plots from which Poisson's ratio was calculated. In order to confirm that the foam did not revert back to its original specifications (creep), the Poisson's ratio of the foam was tested on three separate occasions over a three week period.

The auxetic foam developed for this study showed comparative Poisson ratio values and strain-strain behaviour to other studies in this area by Sanami et al. (2014) and Allen et al. (2015b), figure 4.4. The use of a trend line in figure 4.4 for both auxetic and unconverted foam denotes the average poisson's ratio value, which for the converted foam was -0.38 and is concurrent with other studies listed in Table 2.1. The stress-strain relationship of the auxetic foam (figure 4.6) was found to be similar to the relationship displayed in figure 2.2 from a similar study by Allen et al. (2015b). The behaviour of the converted auxetic foam shows a linear trend with no specific plateau region, because the auxetic cells contract under compression, which is comparable to other studies. Whereas the conventional foam, as predicted, displays a plateau region after a linear region up to a strain of approximately 0.1 (Allen et al. 2015b; Duncan et al. 2016b)

A uniaxial compressive force of just 70N was required to compress the unconverted foam to 70%, which is when the test was terminated. 70N on the other hand only compressed the auxetic foam to 39% of original thickness, which proves that the auxetic foam is more resistant to compressive force. This is significant because the results indicate that the auxetic foam should also resist impact more effectively in comparison to conventional foam. This is discussed further in the next section (4.4).

Harbouring a negative Poisson's ratio means that the converted foam produced adequately contracts under longitudinal compression in the lateral direction, which has already been identified as a behaviour of auxetic material and is comparable to other researches (Sanami et al. 2014; Allen et al. 2015b). Recognising this behaviour of the auxetic foam also confirms that as predicted, around joint areas on the body where it is considered that freedom of movement is required, the ability of the auxetic foam to contract when compressed could reduce pressure on these areas, ultimately leading to improved comfort levels as well as flexibility. This is significant because material characteristics that provide comfort and freedom of movement were highlighted as important features by brands who develop functional competitive aquatic sport clothing (Orca 2015; SigmaSport 2015; Abersochwatersports, 2016; O'Neil 2016; Body glove, 2016). Contraction around joints due to compression, rather than buckling as a conventional material would could also reduce friction resistance during competitive swimming as in theory, it would create a smoother surface. Reducing surface creasing on a macro-level was discussed in the literature review and is directly proportional to reducing frictional resistance (Naemi et al. 2010; Abasi et al. 2013). However, these results are simply an indication to predict this behaviour. To further examine these characteristics, the auxetic foam should be built into a wetsuit garment and a protective vest and tested in real world conditions.

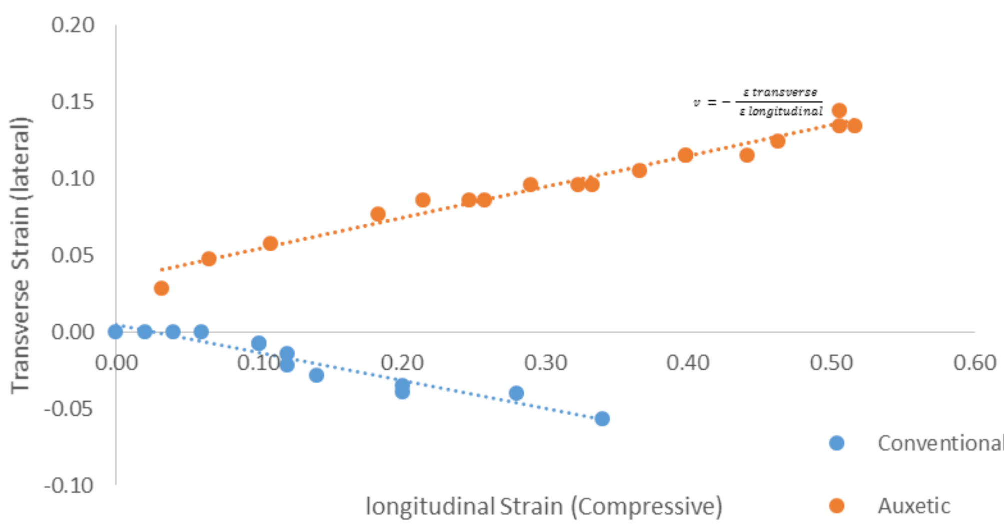


Figure 4.4 Sample compressive strain vs. lateral strain plot with linear auxetic and conventional trend-line

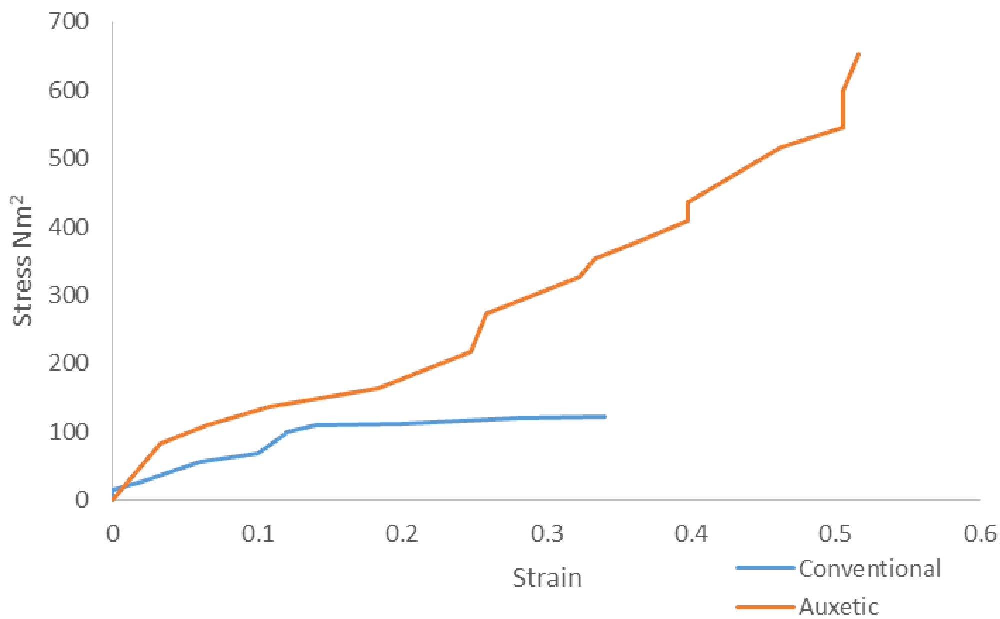


Figure 4.5 Stress-strain plot

4. 4. Impact Attenuation Test Results

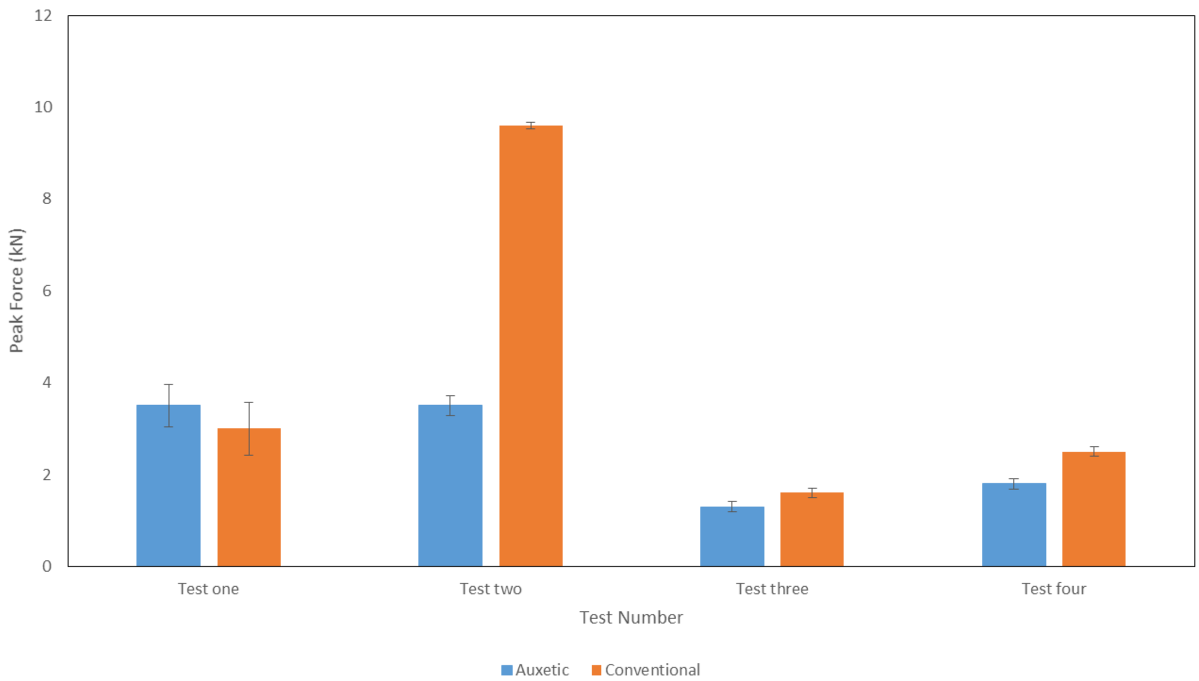
Subjecting the auxetic and conventional foams to impact testing indicates how auxetic materials may enhance such properties in impact protection vests for water sport activities. The compression tests already demonstrated that auxetic foam is more resilient under uniaxial compression. This study examined both auxetic and conventional foams at varying thickness measurements under 5J and 1.5J impacts. The method used is similar to that used by other studies (Sanami et al. 2014; Allen et al 2015a) however the sampling frequency is lower than expected which means the peak impact may not have been accurately recorded. A higher sampling frequency would have produced more concrete, reliable results. Overall, the results proved that the converted auxetic foam experienced reduced peak impact values, in comparison to its conventional counterparts, which corresponds with other studies in this field (Chan and Evans, 1998; Scarpa et al. 2002; Sanami et al. 2014; Allen et al. 2015a).

The original foam, prior to conversion was 50mm thick and when tested under a 5J impact, was found to experience a peak force of 3 kN. Once the foam was converted into an auxetic specimen, thus reducing the foam thickness to 35mm, under the same 5J test conditions, the auxetic foam experienced a peak force of 3.5kN (test one). This is 0.5kN higher than the conventional foam and therefore the peak impacts are similar, almost comparable. However the auxetic foam sample is 30% thinner than the conventional foam, this means that a considerably thinner auxetic version can absorb approximately the same amount of impact. This is significant as a thinner foam is ultimately less restrictive and material that provides freedom of movement was found in the literature review to be an essential characteristic of an impact protection vest for water sport applications (Abersochwatersports 2016; O'Neill 2016; Body Glove 2016).

When examined under a 5J impact at the same thickness measurement of 33mm, the auxetic foam reduces the peak impact by 63% (test two). The auxetic foam absorbs the 5J impact ~2.7 times more improved than the conventional, which is comparable to impact results found by Allen et al. (2015a) and Allen et al. (2015b). Their auxetic foam experienced peak impacts 3 times lower than conventional foam. This means that replacing conventional foam with auxetic foam in an impact protection vest will improve the functionality of the protection qualities by 63%, without using thicker foam. A lightweight material was specified as an essential characteristic of impact vests in the literature review, however although smaller auxetic foams can reduce peak impacts, the density of the auxetic foam has increased during the conversion process. Furthermore, to counteract this, existing techniques such as strategic water draining panels could still be used to lighten the weight of the overall garment.

When subjecting a thinner specimen of 15mm to a lower impact of 1.5J, the mean peak impact measurement was similar for both the conventional and auxetic foam, measuring 1.6kN and 1.3kN respectively (test three). The auxetic foam has only reduced the impact by 19%. Allen et al. (2015b) similarly found that under low impacts (2.2J), the auxetic and conventional foams achieved similar results of resistance, yet as the impact force increased, the resistance of the auxetic foam improved. Therefore, in the context of this study, it is predicted that this behaviour is a result of the conventional foam being suited to adequately absorbing the low impact. For example in this instance, as the conventional structure is not subject to high strains in ratio to its thickness measurement, the foam cells do not collapse as significantly as they do under higher impact forces, as witnessed during test two. Therefore, if the test was conducted on 15mm samples with an impact force between of approximately 3J, it is anticipated that the test results would show a similar pattern to test two, as the auxetic foam should more effectively absorb the higher impact, whereas the conventional foam cells will collapse under such conditions. Building upon this point, reducing the size of the samples to approximately half, proved once again that auxetic foam does absorb impacts more effectively than conventional foam. At 8mm and subject to a 1.5J impact (test four), the auxetic foam experiences a 1.6kN peak impact, which is 16% higher than the impact experienced by auxetic foam when at 15mm. On the other hand, the conventional foam experiences a 1.8kN impact, which is 21% higher than recorded for the same 15mm sample. The results indicate that when the impact force is considered high, in relation to specimen size, auxetic foam performs better. In other words, as the impact force increases, the resistance of auxetic foam increases, which concurs with other researches (Chan and Evans, 1998). Figure 4.9 compares the peak impact results on conventional and auxetic foam for all four tests.

All of these outcomes are in line with previous research as other studies have proven auxetic foams to resist and absorb impact more effectively than conventional foam (Chan and Evans, 1998; Scarpa et al. 2004; Sanami et al. 2014). This behaviour can be explained as a result of auxetic cell geometry under impact, which is discussed in the literature review. However, as the auxetic foam has increased in density during the conversion, it should also be considered that this characteristic can help to reduce peak impacts as found by other researchers (Scarpa et al. 2005). The re-entrant cells directly under the impact compress whilst the rest of the neighbouring cells underneath and beside the compressed cells are drawn in, rather than collapse and deform as seen in conventional materials (Chan and Evans, 1998; Allen et al. (2015b). Therefore, the auxetic foam produced as part of this study is comparable to auxetic foam developed by other researchers, which again proves that the conversion process was successful.



Test One: 5J impact on 35mm auxetic foam and 50mm u/c foam. Test Two, 5J impact on 33mm samples. Test three: 1.5J impact on 15mm samples. Test four: 1.5J impact on 8mm samples. Error bars correspond to one SD either side.

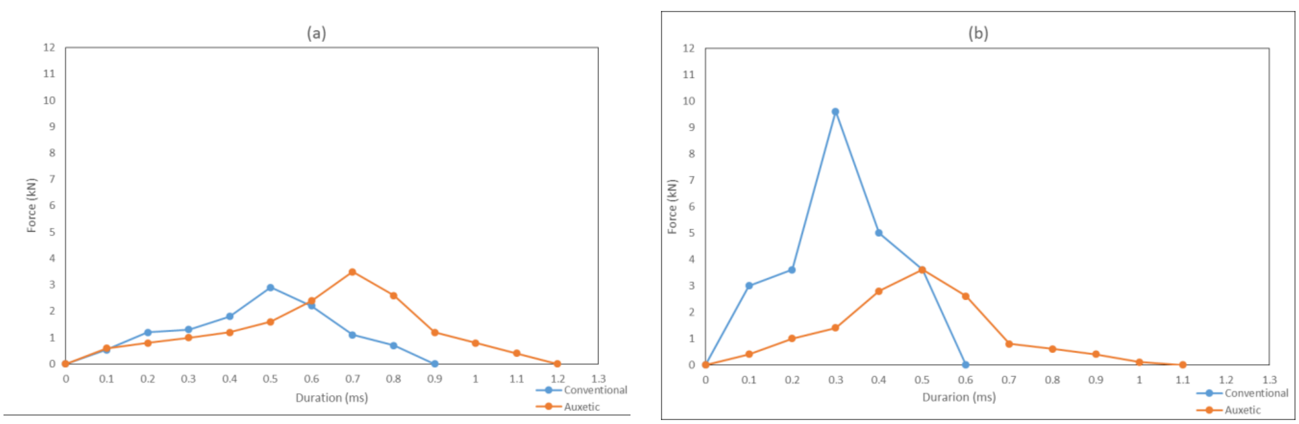
Figure 4.6 Peak acceleration for 5J and 1.5J impact tests on auxetic and conventional foam

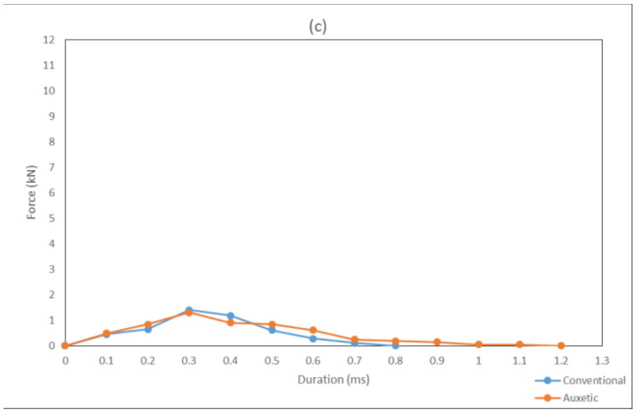
4. 5. Impact Duration Comparison

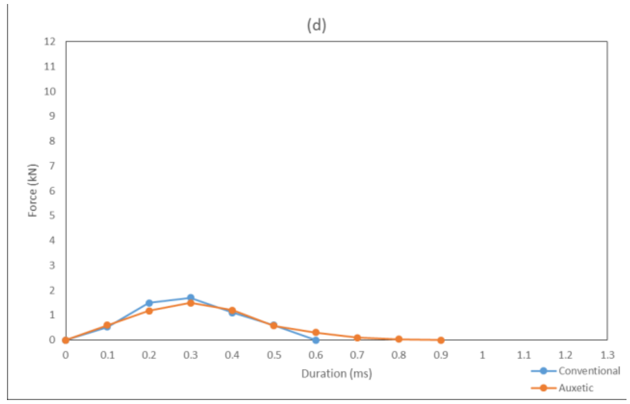
During each of the four test methods, Auxetic foam has a longer impact duration time, which is confirmed by similar studies (Scarpa et al. 2002; Sanami et al. 2014; Allen et al. 2015a). This means that when comparing auxetic foam and conventional foam under the four test conditions presented, the auxetic foam takes longer to reach its peak impact force. The impact time was recorded by visually assessing the test machine output. Results presented are an indication of the length of impact duration. Recording contact time was conducted by visually interpreting the results output from the test machine; once the graph began to rise by three points, this was classed as the initial contact point. Using a high speed camera to record the impact test, as used in other similar studies by Allen et al. (2015) and Duncan et al. (2016a), would have provided more accurate results. However, contact time is very difficult to control and precisely pinpoint even with these measures. For example Allen et al. (2015) found discrepancy between contact times to be maximum 1ms even when analysing frames from a high speed camera. Therefore the results obtained for contact time using the method in this study are considered as supporting evidence.

During each test, the impact duration time for the auxetic foam is between 24% and 57% longer than the conventional foam. Remarkably, during test two and four, where the impact is considered high in relation to the thickness of the sample, the auxetic foam increases the impact duration more significantly, to 40% and 43% respectively in comparison to the unconverted foam. This indicates that when used in a protective vest application, the auxetic foam will extend the impact duration under higher impact strains.

Interestingly, during test three, where a similar value for peak forces were recorded for both 15mm foams under the 1.5J impact, the auxetic foam still increases the duration of the impact by 32% versus the conventional foam. This therefore indicates that the auxetic behaviour of the foam cells are still activated under low impact forces. It is assumed that auxetic cell geometry is mainly responsible for extending the impact duration, though as discussed, increased foam density is also a contributing factor. Figure 4.8 displays the impact duration for both conventional and auxetic foam under all four tests. Chan and Evans (1998) demonstrated that auxetic foam visibly displays wider dispersion of indentation under impact, whereas the conventional foam experiences more local indentation, due to the deformation of the cell ribs. These results indicate that when used in an impact protection vest, auxetic foam has the ability to extend the impact duration as well as reduce the peak impact force.







(a) Test One: 5J impact on 35mm auxetic foam and 50mm u/c foam. (b) Test Two, 5J impact on 33 samples. (c) Test three: 1.5J impact on 15mm samples. (d) Test four: 1.5J impact on 8mm samples.

Figure 4.7 Sample acceleration vs time traces (impact duration) for auxetic and conventional foams.

4. 6. Flexural Rigidity Test Results

Flexural rigidity was undertaken to determine the resistance of foams to bending or also described as, its ability of bending under its own weight. Flexural rigidity is directly proportional to bending length, therefore by monitoring the bending length flexural rigidity can be evaluated. Converting conventional foam to auxetic altered the flexural behaviour of the material. The ability of the auxetic foam to bend under its own weight was improved by 48%, in comparison to its conventional counterpart (table 4.2). Based on these results, it is predicted that auxetic foam will conform to body contours more effectively, as it has proven to be more flexible than the conventional foam. This behaviour is an anticipated result of auxetic materials harbouring a natural synclastic curvature, due to the concave cell orientation. These results are significant as they allow the potential of auxetic foams being used in a compressive garment and impact vest situation to be predicted. As discussed in the literature review, having a negative Poisson's ratio means that when under tension, auxetic foam expands, therefore retaining its shape and not thinning out as seen in conventional foams (Chan and Evans, 1998; Darja et al. 2013; Wang and Hu, 2014). Foams used in a compressive garment are under high levels of tension, and it is anticipated that conventional materials in a highly compressive wetsuit will become thinner and therefore less effective. As discussed in the literature review, academics support that compressing an athlete's body into an improved hydrodynamic shape can significantly reduce pressure and wave drag, leading ultimately to competitive advantage as pressure and wave drag are the two most significant drag forces in competitive swimming (Wu, 2011; Geer et al. 2012; Marinho et al. 2012). Therefore, not only does auxetic foam expand and retain its structure under tension, which suggests it offers superior compression but also from the results of this study, it is proven that auxetic foam has a significantly more enhanced ability to conform to body contours. Again, indicating that auxetic foam can provide improved compression levels. This is significant because improving compression levels in a competitive swimsuit by using auxetic foam that is 48% more effective at contouring to the body has the potential to reduce hydrodynamic drag. Examining this behaviour further should involve testing compression levels when auxetic foams are worn in a garment, however, these results do indicate that auxetic foams show enhanced behaviour.

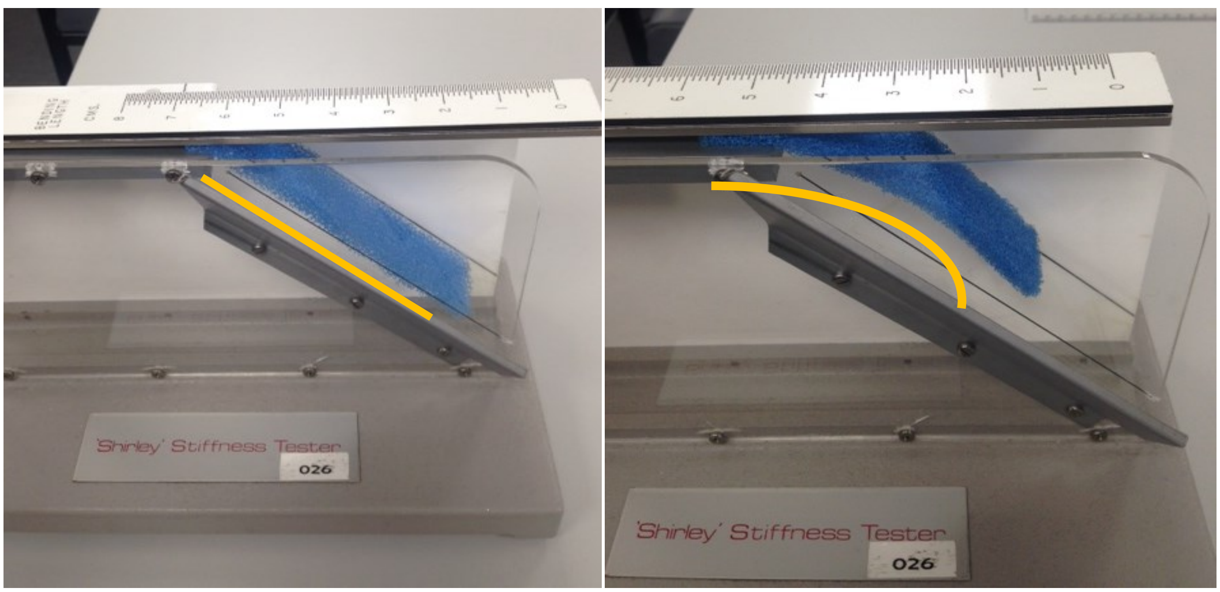
Freedom of movement was highlighted as an important material factor for both watersport impact vests and wetsuits in the literature review. In the case of impact protection vests, as the auxetic foam is more flexible and can conform to the body more effectively, as well as being highly resistant to impact, this suggests that NPR foam could move with body more efficiently, at areas such as under the arms where movement is key, but still provide the highest level of resistance to impact. This is significant as it means that manufacturers would not have to consider using thinner foams in certain areas to reduce movement restriction and therefore ultimately, auxetic foam could enhance the functions of an impact protection vest.

Comfort was also highlighted as a key factor for swimming wetsuits and in the context of this study; it was suggested that cell compression may reduce pressure around joint areas during movement (swimming). However, the flexural rigidity results also prove that the auxetic foam is more flexible and will fit body contours more effectively, therefore it is possible that over joints such as the elbow and knees, as the auxetic foam is under tension and expands in a curved shape, this could provide a greater level of comfort for the wearer. It should be highlighted that these results are regarded as preliminary and in order to further test whether the auxetic foams can improve aspects of freedom of movement and comfort for aquatic sports, they should be built into various garments and 'field tested' in real-life situations.

The difference in bending behaviour between auxetic and conventional foams is evident when visibly comparing both specimens on the testing apparatus. Figure 4.11 clearly illustrates this change in behaviour. As indicated by the yellow line, the conventional foam shows a linear bend over the apparatus platform. On the other hand, the auxetic foam can be seen to display much more of a curved shape (illustrated further with the yellow line) when bending under its own weight. This is significant as the pictures visibly demonstrate that auxetic foams, because of their synclastic curvature, are better suited to conforming to contoured shapes.

Table 4.1 Flexural rigidity and bending length test results

Sample	Sample Thickness (mm)	Bending Length Mean (cm)	Flexural rigidity (µNm)	Difference between auxetic and conventional (µNm)	Improvement from conventional to auxetic (%)
Auxetic	7	4.85	0.436	0.408	48%
Conventional	7	6.99	0.844		



(a) Conventional foam specimen *(b) Auxetic foam specimen*

Figure 4.8 Flexural rigidity testing

The auxetic foam specimens were tested at a 7mm thickness. This was considered an appropriate thickness in the context of this study as wetsuit neoprene foam is generally very thin, though the measurements differ over different parts of the body. This is discussed further in the next section. Around 5mm was originally the desired thickness but as the samples were sliced freehand with a blade, it proved very difficult to accurately cut samples thinner than 7mm. This was mainly due to issues with the conventional foam, rather than the auxetic samples. As the auxetic foam cells are more densely situated together, the sample was more resistant to distorting and pulling during slicing. However, the conventional foam cells collapsed significantly under pressure when trying to hold the sample in place by hand, whilst slicing. Therefore slicing the samples no thinner than 7mm allowed the specimen to maintain consistent to the desired measurements.

To build on this research, it would be interesting to examine the bending behaviour of auxetic foams with differing thickness measurements. From the primary research conducted, it is predicted that when examining thinner samples that have been sliced from larger blocks, there will become a point where the conventional foam will become so thin by loss of cells that it will bend significantly, thus perhaps indicating improved bending capabilities. Whereas the auxetic sample of the same thickness will be a lot more stable due to a higher level of cell retention during slicing, and will not bend as significantly as the conventional foam. However, the conventional foam will not be outperforming the auxetic foam at this point and instead the conventional foam has simply lost its stability due to cell reduction.

4. 7. Speedo Wetsuit Material Evaluation

Conducting the literature review identified that competitive swimsuits including wetsuits, are multifunctional and aimed at reducing hydrodynamic drag. They are designed to compress the body in order to streamline it and reduce surface creasing but must be comfortable and not restrictive, to allow maximum freedom of movement (Mollendorf et al. 2004; Rogowski et al. 2006; Moria et al. 2011; Wu, 2011; Geer et al. 2012; Marinho et al. 2012; Abasi et al. 2013; Orca, 2016; Sigmasport, 2016). To validate these investigations, an assessment of a conventional triathlon wetsuit was carried out. (An image of the wetsuit can be seen in appendix

Three separate materials have been identified in the construction of the wetsuit, figure 4.9 is a diagram of such layers. The foam used within the garment is sandwiched between a layer of knitted fabric and a smooth surface layer.

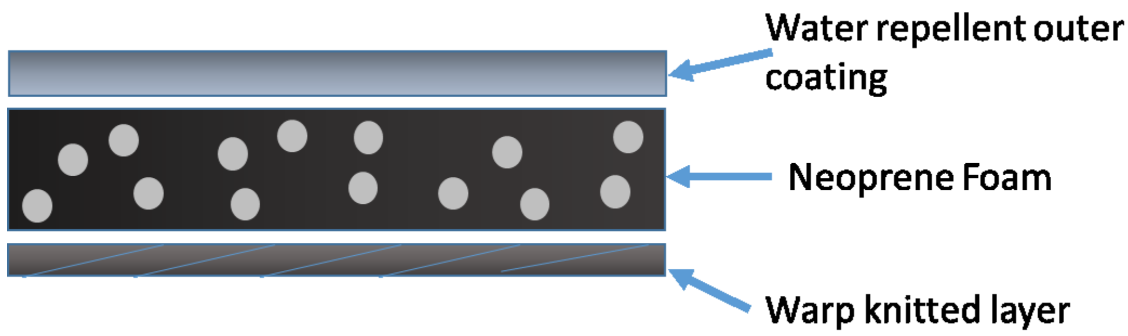


Figure 4.9 Wetsuit material layers

4.7.1. Layers One and Two: warp knitted fabric and water repellent coating

Firstly, a warp knitted layer has been bonded to the foam. The first warp knitted layer sits between the skin and the foam, therefore the attributes of the fabric are that is it smooth and comfortable next to the skin. The care label states that the knitted warp layer is Polyamide.

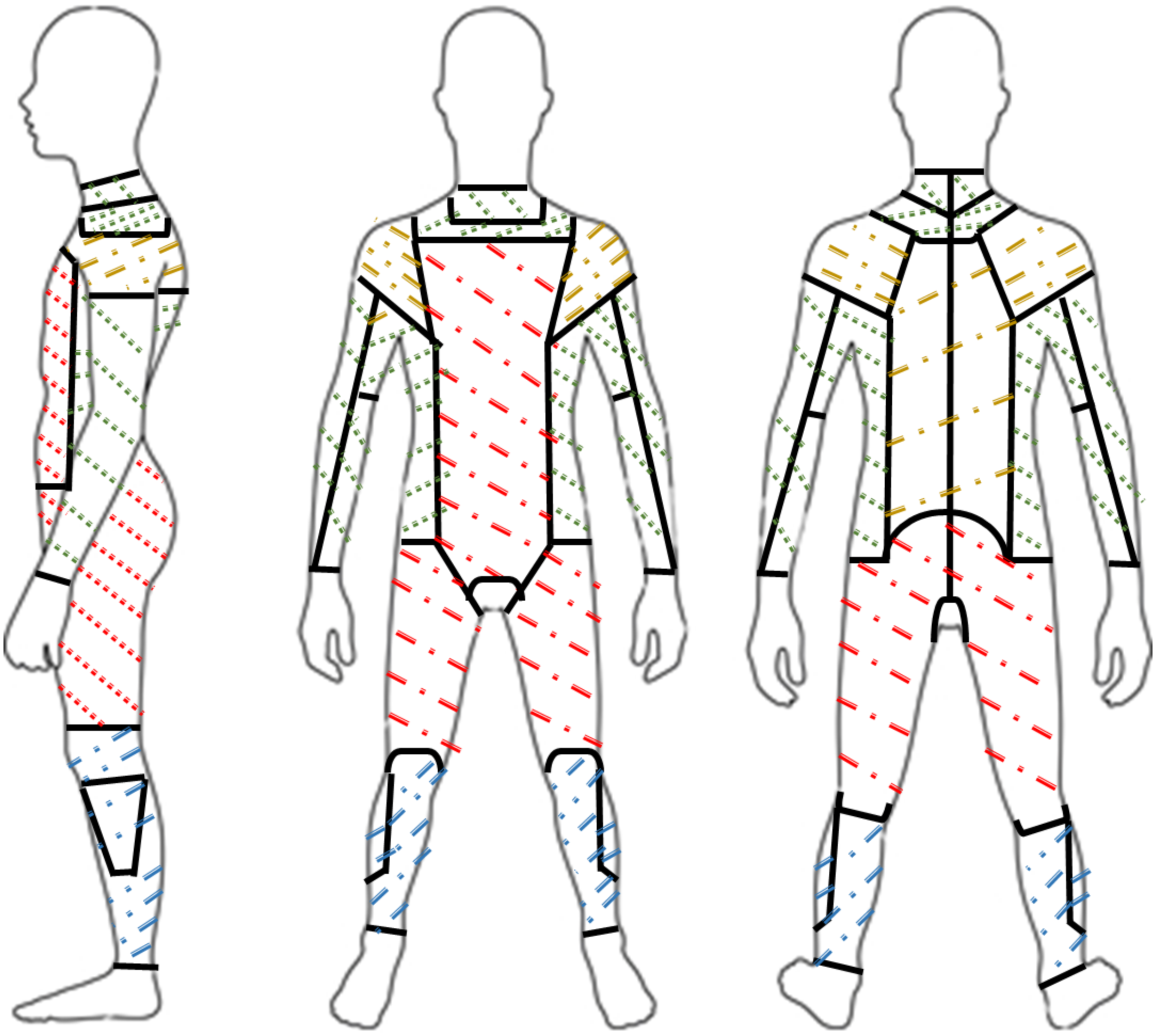
The foam has then been bonded to a finishing layer to form the outer layer of the material, this is in direct contact with the water when swimming. The third layer which is in the form of a coating is very smooth to touch and when observed using the piece glass. As this layer will interact directly with the water, the smoothness indicates that the finishing has been applied with the intention of reducing friction resistance. A macro-level smooth material surface is recognised in literature as a friction drag reducing characteristic and so the material surface is coherent with this theory (Naemi et al. 2010; Abasi et al. 2013). When tested for water repellency, the top coating was repellent to an average value of 80 (ISO 4), which indicates that the neoprene fabric is water repellent to a high level. This is significant as Rogowski, et al. (2006) found that a water repellent outer coating or finish to a material will reduce friction resistance during passive drag. This therefore proves that the Speedo wetsuit is designed to reduce friction drag. (Full test results for spray rating and an image of the results can be seen in appendix H.)

4.7.2. Layer Two: Foam

The second layer, which is the foam itself, varies in thickness depending on what part of the garment it sits in. The most appropriate way of assessing the thickness of various panels built into the garment, for example the thigh panels, was to take a reading for a double, folded over layer, then divide the measurement by two to get a reading for a single layer. This approach was tested in areas where a single layer could be easily tested, for example at arm and leg opening, to ensure that the readings were accurate and repeatable. The foam ranged between 2mm and 5mm throughout the different panels of the wetsuit, figure 4.13. Side panels underneath the arm joint and down the side of the body and at the neck were much thinner (2mm) and therefore much more flexible than the foam found along the torso and thighs (5mm). Their placement within the garment and in line with information sourced from the literature review, suggests that the foam is strategically thinner to improve functionality. Freedom of movement and comfort were highlighted in the literature review as key material characteristics in a compressive swimming garment (Shishoo 2005; Manshahia and Dasa, 2014 Orca, 2015; Sigmasport, 2015) and in theory; the thinner panels will allow improved flexibility without being restrictive and therefore providing comfort in comparison to more restrictive materials. The test results and discussions from sections 4.4 and 4.5 have already been found to have the potential to increase freedom of movement and improve comfort, therefore in line with the wetsuit assessment, auxetic foam could be placed at the arm joint, down the side of the body and round the neck for flexibility. (Appendix I. displays the full set of thickness measurement test results.)

In the literature review, it was found that targeted compression of certain body areas and in particular, the torso, legs and buttocks can reduce pressure drag (Wu, 2011; Marinho et al. 2012). In the wetsuit tested for the purpose of this study, the foam material in these zones was found to be at its thickest (5mm) on the thigh, torso and buttocks panels. This indicates that the suit has been designed to further compress these areas and counteract the material thinning out under tension.

These results specify where high compression zones are placed and therefore indicate where auxetic foam may be advantageous. As the results from the flexural rigidity testing have shown, auxetic foam has the potential to conform to body contours much more effectively than conventional foam, it was therefore suggested that in a competitive wetsuit, auxetic foam would provide adequate compression, without thinning out, especially in targeted areas like the torso, thighs and buttocks. This means that separate 'thicker' areas would no longer be needed and the garment could be created with less panels, resulting in fewer seams, which could further reduce hydrodynamic drag as the wetsuit surface would be completely smooth and uniform, without seams.



Key

Colour indicator	Foam Thickness Measurement
	5mm
	4mm
	3mm
	2mm

Figure 4.10 Conventional wetsuit material panels

Chapter 5. Conclusion and Recommendations

This chapter presents the conclusions obtained by conducting the research process in line with the study aims and hypotheses. Recommendations for further research that became apparent whilst conducting this study are also highlighted.

5.1.1. Aim One

To critically appraise auxetic materials (foams and textiles) for their potential, performance and behaviour for competitive aquatic sport applications.

The first aim was achieved through secondary research by way of conducting a literature review. Firstly, auxetic behaviour was examined. Secondly, auxetic manufacturing techniques suited to competitive aquatic sports were researched. An enquiry into the resultant behaviour of negative Poisson's ratio materials found that they harboured many unique characteristics, some of which have the potential to enhance competitive aquatic sporting situations. Auxetic materials were found to provide improved resilience to strain and indentation, (Chan and Evans, 1998; Scarpa, 2002; Sanami et al. 2014; Allen et al. 2015a;) which is particularly suited to protection vests for water sports such as kitesurfing and windsurfing, as they are designed to protect the athlete from impact. The auxetic property of synclastic curvature (Alderson and Alderson, 2007) was also of interest in the context of competitive swimming wetsuits as it presents an ability to conform to contours and competitive wetsuits are compression garments. The factors affecting both of these sporting situations were examined further in aim two. Achieving aim one therefore adequately provided an initial insight into the possibility of developing auxetic materials to enhance such sporting events.

Investigating various manufacturing techniques highlighted that auxetic textiles were not advanced enough at the time of this study to be developed for this project because researchers found that the most progressive auxetic textile structures reverted to positive Poisson's ratio materials at medium to high tension levels (Hu et al. 2011; Ugbolue et al. 2011; Alderson et al. 2012). Therefore instead, a theoretical analysis based on available literature was provided. Auxetic foams on the other hand, were found to be much more advanced in terms of having a viable route to manufacture on a small-scale for laboratory testing purposes. Therefore, the creation and testing of auxetic foams was the focus of the study.

The literature search highlighted that authors such as Sanami et al. (2014) have suggested the use of auxetic foams for sporting equipment but not necessarily for use within sports garment, specifically for competitive aquatic sports. In the context of this research, auxetic foams had never been examined for their behaviour or response over contoured body shapes.

The original thermo-mechanical conversion process was considered most appropriate for this research (Lakes, 1978). Other researchers such as, Chan and Evans (1997); Sanami et al. (2014); Allen et al. (2015b) and Duncan et al. (2016a;2016b) have since refined the process developed by Lakes in order to reduce and avoid conversion issues such as, creep and surface creasing with the resultant material. Major break-through research in relation to the thermo-mechanical process was documented. For example, Chan and Evans (1997) found reducing the size of large foam specimens through incremental compression stages significantly avoided creep occurring and minimised surface creasing. Sanami et al. (2014) and Allen et al. (2015b) similarly found that exposing the foam to constant compression and subjecting the specimen to three differing time and heat stages yielded successful results and was particularly suited to specimens of smaller dimensions (starting measurements between $100mm^2$ and $143mm^2$). The foams used in such studies were of similar dimensions and specification to the foam converted for this study. Collecting this information therefore enabled a unique manufacturing process to be successfully developed for the purpose of this research. Furthermore, revolutionary research by Duncan et al (2016a; 2016b) introduced through-pins to the compression mould to further eliminate surface creasing and maintain linear compression ratio in all three planes when producing thinner samples, which were of particular interest to this study. However, the process outlined by Duncan et al. (2016a; 2016b) was still considered at foetal-stage and although specimens produced were considered thinner, they were still too thick for the purpose of this research and therefore converting larger blocks (where surface creasing is reduced) and slicing to smaller dimensions was more appropriate at the time of conducting this research.

5.1.2. Aim Two

To analyse contextual factors that influence the performance of athletes in competitive aquatic sports.

The second aim was also met through the process of a literature review. This aim was focused on determining the effect of hydrodynamics on swimming and the purpose of impact protection vests. Secondary research methods accomplished aim one and two and generated a body of knowledge to develop hypotheses that were subsequently evaluated in the laboratory.

Ultimately, it was found that an impact protection vest is designed to safe-guard against high-speed collisions during water sports such as windsurfing and kitesurfing. However, it was also found that garments should provide adequate freedom of movement and be as lightweight as possible whilst being primarily protective (Abersochwatersports, 2016; Body glove, 2016; O'Neil, 2016).

Hydrodynamic resistance during competitive swimming was found to measure 500-600 times more than a body moving through air and ultimately to cost the swimmer '90%' of their power output. It was acknowledged that improving swimming performance was largely based upon the athlete's physique and swimming technique but that there is also significant potential for swimming attire to enhance swimming performance (Taiar et al. 1999; Mollendorf et al. 2004; Pendergast et al. 2006; Moria et al. 2010). Due to this potential, competitive swimming wetsuits and swimsuits are designed to improve performance by further reducing hydrodynamic drag (Blazevich 2010; Voyce et al. 2010; Wu, 2011).

Studies have found that adequate bodily compression and an ultimately smooth surface to the suit can significantly reduce pressure, wave and friction resistance (Mollendorf et al. 2004; Rogowski et al. 2006; Moria et al. 2011; Wu, 2011; Geer et al. 2012; Marinho et al. 2012; Abasi et al. 2013). Therefore, the next stage of the research was to develop and examine auxetic materials in line with these findings of factors that influence both competitive swimming and impact resistance attire for watersports. In other words, auxetic materials collectively (textiles and foams) were reviewed for their potential to reduce hydrodynamic drag during competitive swimming and improve impact resistance in water sport protection vests.

5.1.3. Aim Three

To develop auxetic foams and assess their suitability, behaviour and potential in competitive swimming wetsuits and water sport impact protection vests.

Aims one and two informed the development of hypotheses in order to accomplish the third aim. The hypotheses were focused on developing auxetic foams, assessing their similarity to previous studies and examining their behaviour in order to assess how they may improve the functions of both impact water sport vests and competitive swimming wetsuits.

Hypothesis 1*:* New auxetic foams can be developed from manufacturing techniques adapted from existing methods. (Auxetic foams can be engineered to suit real-world situations).

The thermo-mechanical manufacturing method identified and developed as part of Aim One was put to test. A compressive mould needed to be designed and developed in order to adequately compress the foam by 0.7 LCR in each of the three planes. The mould was successfully produced in-house and the conventional foam was subsequently converted to auxetic foam under laboratory conditions. However, the resultant foam was found to lack homogeneity and therefore the results of subsequent performance testing are unreliable. Surface creasing due to insertion into the conversion mould caused the foam to convert unevenly, this is a common issue found by other researchers (Chan and Evans, 1997). More advanced conversion processes to avoid surface creasing, such as the studies by Duncan et al. (2016a; 2016b) should be considered in future research to eliminate this issue. The converted foam was examined in a laboratory using a compressive strain method and was found to have a negative Poisson's ratio of -0.13 at 15% compressive strain and -0.17 at 10% compressive strain. These results are in line with previous researchers using similar foam specifications, compression ratios and methods of conversion (Sanami et al. 2014 and Allen et al. 2015b). Another common issue when manufacturing auxetic foams is the onset of creep (Chan and Evans, 1997) however, the unique conversion method successfully developed stable auxetic foam that did not revert back to its original specifications.

The remaining three hypotheses were concerned with the behaviour of the converted auxetic foam and its potential application to aquatic watersports. Converting thin auxetic foams is preferable to examine their potential for wetsuit and impact vest applications but it was predicted that it would be difficult to produce thin foams due to the difficulty in maintaining a compression ratio in the unilateral direction, therefore larger foam samples were produced and sliced to smaller dimensions.

Hypothesis 2: Auxetic foams provide enhanced resistance to impact in watersport protection vests.

The auxetic foam proved to resist uniaxial compression more effectively than the conventional foam, suggesting that it should resist impacts more effectively. Subjecting the auxetic foam to impact testing validated this prediction and results were in-line with other studies from the literature review (Chan and Evans, 1998; Scarpa et al. 2004; Sanami et al. 2014, Allen et al. 2015b). The converted auxetic foam reduced peak impact values between 19% and 63%, depending on force and foam thickness. Complementing these results, auxetic foam also extended the impact duration time by between 24%-57%, which is again in-line with previous researches (Scarpa et al. 2002; Sanami et al. 2014; Allen et al. 2015a).

Hypothesis 3*:* Auxetic foams enhance compression zones in competitive swimming wetsuits. Initial recommendations can be made as to where these 'zones' should sit in a garment.

As found under aim two, compression of bodily parts such as the buttocks and thighs can improve swimming performance by reducing hydrodynamic resistance of the athlete (Mollendorf et al. 2004; Wu, 2011; Geer et al. 2012; Marinho et al. 2012). Therefore, auxetic foams developed were investigated for their potential to enhance these compression zones in comparison to conventional foams.

The flexural rigidity testing results (section 4.5) proved that the auxetic foam has the ability to conform to body contours 48% more effectively that conventional foam. The results suggested that auxetic materials are therefore expected to provide more enhanced compression in garment situations. Primary research highlighted that thicker neoprene material in key compression zones is used in conventional competitive swimming wetsuits. Under uniaxial tension, conventional materials become thinner, whereas auxetic materials are proven to experience a volume change in the way of expansion, this combined with the ability of the auxetic foam to conform better to the body contours indicates the positive potential of auxetic foams to be used in wetsuits, particularly to compress key areas. Auxetic foams could therefore more accurately provide enhanced targeted compression in swimming wetsuits.

Hypothesis 4: Auxetic foams improve comfort and freedom of movement for watersport protection vests and competitive swimming wetsuits. Initial recommendations can be made to advise where these areas sit in a garment.

The test results from the primary research indicated that auxetic foam could enhance freedom of movement in key joint areas, for both sports, where dynamic movement is experienced. The literature review conducted under aim two of the study identified freedom of movement as a key material characteristic for both sports, and comfort was recognised as important particularly when researching competitive swimming (Orca, 2015; Sigmasport, 2015; Aberscohwatersports, 2016; Body glove, 2016; O'Neill, 2016). When subjecting the converted foam to compressive strain, it was clear that as the Poisson's ratio of the material was negative, a key auxetic behaviour began to occur. The foam cells began to contract, which suggests that in a wetsuit application, at the back of the knees for example; the auxetic material would contract when under compression due to joint movement and could subsequently reduce pressure in this area, leading to an improvement in comfort. Contraction of cells at joints also indicates that the material would stay smoother on the surface, rather than bulking as conventional materials do when compressed. This therefore allows the prediction to be made that auxetic foams could present a reduction in friction resistance, as a smooth 'crease free' material surface was found in the literature review conducted under Aim Two to reduce surface friction (Mollendorf et al. 2004; Rogowski et al. 2006; Moria et al. 2011; Abasi et al. 2013). This aspect should be examined further, as these results only allow a prediction of this behaviour.

Examining the auxetic foam for flexural rigidity also proved that the auxetic foam was more suited to conforming to contours due to its inherent synclastic curvature. This behaviour, combined with the fact that under tension, auxetic materials expand, suggests that again at joint areas, auxetic foam could provide enhanced freedom of movement.

5. 2. Recommendations

The project examined the potential, performance and the behaviour of auxetic foams for apparel application in particular for competitive aquatic sports. This study is an evolving piece of work and the conducting research has presented opportunities for further academic studies in this area. The current exploration has signposted an opportunity to further determine the suitability of foams being embedded in garments and to investigate the potential in real life circumstances.

The study presented opportunities for further testing to understand how the contraction of auxetic foam cells under compression can help to reduce hydrodynamic resistance by reducing friction resistance. This could involve assessing the friction drag over the auxetic foam in various positions that would occur during active swimming to gain a further understanding of their potential.

Embedding auxetic foams into a competitive swimming wetsuit garment is also recommended as an opportunity for future research. As a progressive next step forward for this study, compression zones could be tested to accurately evaluate levels of compression of auxetic foams against conventional materials.

Developing thin auxetic foams is desirable for this type of research as the competitive wetsuit assessed for this study was made from neoprene that was between 3mm and 5mm. However, producing thin auxetic foams is predicted to be complicated and problematic using the thermo-mechanical method as it is difficult to maintain the compression ratio in the lateral direction due to the sample being so thin. Producing larger, stable specimens and slicing thin samples on the other hand achieves the desired dimensions but in the process cell are lost as they are cut away. Outside of this study, the literature review revealed the through pin compression method by Duncan et al (2016) produced the thinnest samples (30mm) without the need for slicing, though they were still too thick or the purpose of this research. Therefore there is scope for perfecting the conversion technique to achieve thinner foams in the future.

The impact resistance testing results indicated the potential for the use of auxetic foams within impact resistant water sport vests. The specialised nature of this research does also present other areas where these materials could be utilised for similar applications. Future testing could include applications within the medical industry for example, in the development of broken bone casts. Manufacturing unique NPR foams finely tailored to the end application could be widely addressed. Exploring the manufacturing technique further should lead to the possibility of creating auxetic foams for specific functions. For example, increasing the negative Poisson's ratio value of the converted foam in order to provide a higher level of impact resistance where it is needed in impact protection vests.

Based on the current exploration, the project indicated the potential for auxetic foams to be part of the aquatic sports garment, the next stages should focus on tailoring the auxetic foams into moulded body shapes and testing its efficacy. There remains a need to develop a conversion technique to manufacture auxetic foams of varying thickness.

5.2.1. Limitations

Research involving the development and wide application of auxetic materials for aquatic sportswear is on-going and in foetal stages. Although the results are still considered valid and reliable, desired test methods, such as quasi-static testing to evaluate Poisson's ratio of converted samples, would have enabled more samples to be developed and tested and therefore a wider range of test results. Future developments should continually explore various avenues particularly with regard to developing materials that harbour unique auxetic behaviour and evaluating their potential for sports and protective-wear.

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Appendix

A. Foam specifications

	Auxetic	**Unconverted**
Construction	Open cell, reticulated	Open cell, reticulated
Material	Polyurethane	Polyurethane
Density	5.018 gm^3	0.258 gm^3
Pores per inch	30 PPI	30 PPI
Poisson's Ratio under compressive strain	-0.13 at 15%	0.13 at 11%

B. Impact attenuation test results

Auxetic Foam Testing 1.5j impact	
35mm	
Sample	Peak force (kN)
1	0.553
1	0.541
1	0.541
1	0.541
1	0.602
Mean	0.556
STDEV	0.03
STDEV %	4.8

Auxetic Foam Testing 5j impact	
35mm	
Sample	Peak force (kN)
1	3.257
1	2.888
1	3.54
1	3.65
1	4.154
Mean	3.498
STDEV	0.47
STDEV %	13.5

Conventional Foam Testing 1.5j impact	
50mm	
Sample	Peak force (kN)
1	0.479
1	0.504
1	0.504
1	0.504
1	0.504
Mean	0.499
STDEV	0.01
STDEV %	2.2

Conventional Foam Testing 5j impact	
50mm	
Sample	Peak force (kN)
1	2.274
1	2.962
1	3.626
1	3.528
1	2.655
Mean	3.009
STDEV	0.57
STDEV %	19.1

Auxetic Foam Testing 1.5j impact	
15mm	
Sample	Peak force (kN)
1	1.315
1	1.18
1	1.315
1	1.278
1	1.512
Mean	1.320
STDEV	0.12

Auxetic Foam Testing 5j impact	
33mm	
Sample	Peak force (kN)
1	3.81
1	3.441
1	3.417
1	3.614
1	3.257
Mean	3.508
STDEV	0.21

Conventional Foam Testing 1.5j impact	
15mm	
Sample	Peak force (kN)
1	1.586
1	1.389
1	1.364
1	1.401
1	1.536
Mean	1.455
STDEV	0.10

Conventional Foam Testing 5j impact	
33mm	
Sample	Peak force (kN)
1	9.489
1	9.648
1	9.55
1	9.636
1	9.612
Mean	9.587
STDEV	0.07

STDEV %	9.1

STDEV %	6.0

STDEV %	6.8

STDEV %	0.7

Auxetic Foam Testing 1.5j impact	
8mm	
Sample	Peak force (kN)
1	1.758
1	1.45
1	1.573
1	1.573
1	1.524
Mean	1.576
STDEV	0.11
STDEV %	7.2

Conventional Foam Testing 1.5j impact	
8mm	
Sample	Peak force (kN)
1	1.893
1	1.93
1	1.844
1	1.881
1	2
Mean	1.844
STDEV	0.10
STDEV %	5.5

C. Flexural rigidity and bending length results

To find mass per unit area;

$$M \div (L \times W)$$

Where:

M = Mass

L = Length

W = Width

Foam type	Dimensions (m)			Weight (g)	mass per unit area (gm2)	mass per unit area (g/m2)
unconverted	0.15	0.03	0.7	0.91	0.00363	251
Auxetic	0.12	0.03	0.7	1.18	0.003025	390

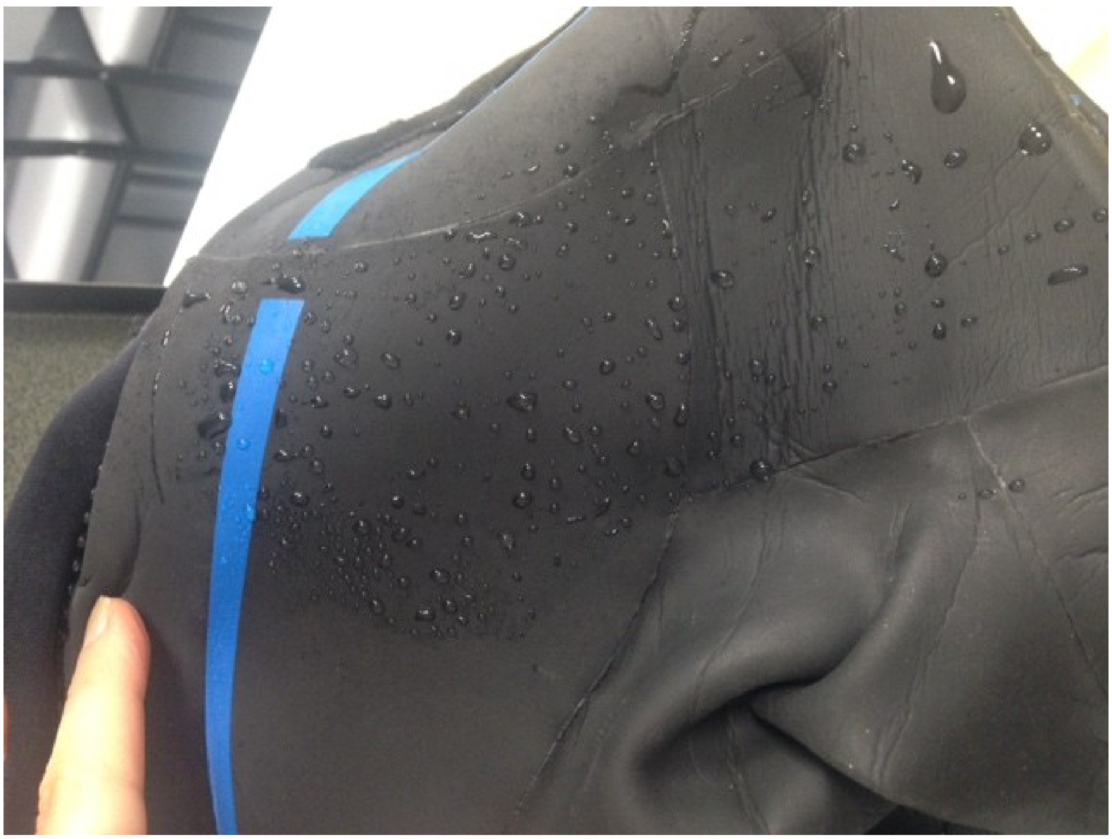
Sample	Bending Length (mm)	Flexural rigidity µNm
auxetic	4.85	0.436
conventional	6.99	0.844

D. Speedo Wetsuit Images

Wetsuit Front	Wetsuit Back

E. Spray rate testing results and image

Test number	1	2	3	4	5
Test score	4	4	4	4	4



F. Wetsuit thickness panel measurements

	measurement in mm			Mean	STDEV		double in mm			Mean	STDEV
front right lower leg	3.50	3.48	3.55	4	0.04		7.31	7.35	7.33	7	0.02
Right leg panel	3.73	3.71	3.73	4	0.01		7.45	7.42	7.45	7	0.02
front left lower leg	3.54	3.48	3.54	4	0.03		7.08	6.96	7.08	7	0.07
Left leg panel	3.75	3.74	3.73	4	0.01		7.50	7.48	7.45	7	0.03
front right thigh	4.75	4.75	4.77	5	0.01		9.50	9.50	9.54	10	0.02
front left thigh	4.76	4.75	4.76	5	0.01		9.52	9.49	9.52	10	0.02
torso	4.70	4.70	4.75	5	0.03		9.40	9.40	9.50	9	0.06
shoulder left	2.66	2.72	2.70	3	0.03		5.40	5.45	5.40	5	0.03
shoulder right	2.70	2.75	2.70	3	0.03		5.40	5.45	5.35	5	0.05
arm right	1.90	1.88	1.98	2	0.05		3.80	3.76	3.96	4	0.11
under arm right (lower)	1.95	1.90	1.93	2	0.03		3.90	3.80	3.85	4	0.05
arm left	1.95	1.85	1.90	2	0.05		3.90	3.70	3.80	4	0.10
under arm left (lower)	1.93	1.85	1.85	2	0.04		3.85	3.70	3.70	4	0.09
Back left	2.75	2.80	2.75	3	0.03		5.50	5.60	5.50	6	0.06
Back right	2.84	2.80	2.75	3	0.05		5.68	5.60	5.50	6	0.09
under arm right	2.15	2.15	2.10	2	0.03		4.30	4.30	4.20	4	0.06
under arm left	2.15	2.20	2.10	2	0.05		4.30	4.40	4.20	4	0.10
Inner neck	2.20	2.15	2.20	2	0.03		4.40	4.30	4.40	4	0.06
Upper neck	2.10	2.20	2.15	2	0.05						