ENGR9700 Masters Thesis

Optimisation and impact assessment of novel protective guards used in cricket

by

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Declaration

I certify that this work does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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October 2019

Abstract

Concerns about injury in cricket have been reported as a leading reason why participants choose to leave the sport (Sport Australia, 2019). With a 163g ball bowled at high speeds of up to 160km/h, batsmen are particularly vulnerable to impact trauma, ranging from contusions and fractures, to fatal tragedies that question the safety and public perception of the sport. While there has been great emphasis and progress in the development of helmets and shin pads, protection of other body parts have not been thoroughly evaluated or analysed in literature.

This project is driven by a client with the aim of evaluating the protective properties of Isoblox, which is a thin, hexagonal mesh material that provides impact dispersion properties. Isoblox has successfully returned promising results in previous testing carried out by Ziegler (2016) in the United States, with comparison against padding from other reputable competitors showing a clear improvement. This thesis extended the impact assessment of the original Isoblox material, as well as three newly formed Isoblox compositions, in various configurations involving five different types of ethylene-vinyl acetate (EVA) or polyethylene (PE) foams.

A testing protocol has been developed to apply impact energy in a drop test setting that is equivalent to that experienced in a competitive cricket game. While similarities can be drawn between this protocol and the official standard, BS 6183-3:2000, a key difference in this study is the use of ballistics gelatine, on which the materials are tested. This deformable layer imitated soft tissue in a human limb, and allowed for a more realistic simulation of the impact event. Due to the inclusion of this layer, new observations about the material could be made upon visual inspection, such as the potential for various types of damage. These characteristics were not previously identified in testing, and have prompted ideas for material improvement by strengthening the interconnecting hinges in the mesh.

The combinations of interest were selected in collaboration with the client, and force data from drop tests were collected using a 20kN capacity load cell, recorded at 5kHz. Data acquisition was completed using the National Instruments SignalExpress

software, and analysis was completed in MATLAB. The key parameter evaluated from the data was the peak force transmitted through the sample, which was taken from the maximum force of the first bounce of the impactor on the material. Peak forces were compared to draw conclusions about the best performing Isoblox composition, foam type, and lay-up configuration. From these results, the most effective materials were re-tested to assess repeatability, finding a range of variation between 148N – 1024N. The best-performing materials were then combined to create two superior lay-up configurations, with input from the client to ensure that the materials meet the requirements of flexibility and thickness required for a protective guard. The new combinations were found to provide the most protection out of all materials tested, with peak transmitted forces of 3974N and 4496N. This is a respective 2466N and 1944N less than the next best configuration. Since this is outside the range or variation found in the repeatability tests, it can be said that this is a significant improvement, although further repeats of testing would be recommended to properly distinguish between the best two configurations. Unlike all other samples, the best two material configurations were also successful in protecting the underlying ballistics gelatine from visible damage. Overall, the thesis presents an evaluation of protocols for sports guard impact testing, highlights the optimal materials that may be considered for further development, and provides many areas of improvement to be implemented in future testing.

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Chapter 1. Introduction

1.1 Background

According to Sport Australia (2019), cricket is one of the most popular sports in the country, with participation rates predicted to increase in future seasons, particularly among children. Unfortunately, the injury rates reported for the sport are concerning, especially for batsmen who face the highest risk of being accidentally struck by the ball. Considering the high speeds at which the ball is typically delivered by the bowler, impact injuries such as swelling, contusions, and fractures are frequently reported in media during the cricket season. In particular, the controversial death of Australian cricketer Phillip Hughes in 2014 following a blow to the vertebral artery in the neck has drawn significant attention to the inadequacy of protective sports equipment (Keane, 2018). Although considerable research has been undertaken to improve head protection provided by helmets, there has been comparatively little emphasis on the evaluation of body protection in literature.

This project was driven by a client who has an entrepreneurial background in the sporting industry, with a desire to test cricket protective guards for the chest, forearm and upper leg. The material of interest is known as Isoblox, which is a protective mesh sheet comprising of hexagonal plates and connecting hinges, patented by Dodd (2015). Initial testing data has shown that this material has superior impact dispersion properties, compared to reputable competing brands such as McDavid, Nike, Under Armour, G-Form and Evo Shield (Ziegler, 2016). The client's goal was to obtain data from a comparison test to validate this initial study, as a critical step in the product development and commercialisation processes. While this project focused solely on the application of the guards in cricket, the client has expressed a desire to eventually adapt the technology for other sports and applications as well.

The client provided five different types of ethylene-vinyl acetate (EVA) and polyethylene (PE) foams, and four different compositions of Isoblox for testing, in order to identify the material configuration that provides the most effective protection. This was assessed by conducting drop tests on each configuration, and comparing the resulting peak force transmitted during impact. The results of this study will be implemented in further product development, with the optimal material configuration being used for prototyping.

1.2 Aims and objectives

The aims of this thesis include:

- Establishing a drop testing protocol that accurately replicates the typical energy received in a competitive cricket match.
- Conducting tests to obtain data that describes the peak transmitted force for all material configurations of interest.
- Analysing data on a comparative basis to identify the material configuration that provides the most effective protection.

In order to devise a thorough and reliable protocol, the testing methods used previously by Ziegler (2016) and the official standard that outlines the requirements of protective equipment for cricketers (BS 6183-3:2000) were consulted. Measures were taken to better replicate the material response on a human limb, in order to improve the accuracy of testing conditions. While it was important to ensure that testing conditions were as realistic as possible, note that the material configurations are assessed on a comparative basis. The material configurations of interest were decided with significant input from the client, who was consulted about what combinations would be suitable in terms of practicality and player comfort.

The main objective is to establish trends that highlight the best configuration of materials for the future development of an optimised prototype Isoblox guard. The project intends to contribute to the client’s goal of providing more effective cricket gear to players of all ages and skill levels, in an effort to reduce risk of injury and therefore encourage prolonged participation in the sport.

Chapter 2. Literature Review

Although cricket is not considered a contact sport, impact injury poses a significant risk, whether cricket is being played recreationally and competitively. With the ball being bowled at speeds up to 160km/h, the batsman receiving the ball is particularly at risk of injury from ball collision, along with the wicket-keeper and nearby fielders (Pardiwala *et al.*, 2017). Scoring runs requires mobility and freedom of movement, therefore making it crucial that any protective equipment worn is comfortable and does not limit performance.

The purpose of this literature review is to identify the current types and occurrence of injuries in cricket, gain insight into the testing and development that has been undertaken to improve protective equipment worn by cricket players, and analyse new testing protocols that may prove to be more effective in evaluating the performance of protective equipment.

2.1 Participation rates and market growth in Australia

As one of Australia's most popular sports, cricket attracts participants of all age groups and is a growing part of Australian culture. This has been well documented by Sport Australia through their AusPlay survey, which is the most comprehensive collection of sports data for the national population (Clearinghouse for Sport, 2019). In the most recent cricket state-of-play report, Sport Australia (2019) found that 2.7% of adults and 5.5% of children currently play cricket, totalling 798,619 participants in the country. The majority of this figure is actually paid to participate in cricket, with the annual cost totalling to $126 million, and 79% of players consider cricket to be their most strongly associated sport. This commitment and loyalty to the sport is indicative of the opportunities for growth in this market, and potentially a willingness to spend to improve the sport and increase participation. The net market growth has been slow and steady over the last couple of years, with the AusPlay survey results predicting a 4% increase in adult participation, and a 21% increase for children in the coming year (Sport Australia, 2019).

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Figure 1: Participation in organised cricket by life stage. Reproduced from Sport Australia (2019).

Participation levels peak in the age group of 9-11 years old, after which it gradually decreases until adulthood (Figure 1). While the leading motivations for playing cricket are enjoyment and social reasons, the reasons for leaving the sport are lack of time amongst other commitments, as well as injury or health concerns (Sport Australia, 2019). Interestingly, only 10% of all Australian participants are female, making cricket a heavily male-dominated sport. The 2018-19 Annual Report from the International Cricket Council (ICC) announced a new international Women's Committee to encourage further opportunities for females in cricket (ICC, 2019a). This highlights a clear desire to promote greater involvement of women and girls in cricket.

The hindering factor of injury and health concerns raises questions about whether further advancements in injury prevention may encourage prolonged participation for all players, and whether it would aid in raising the participation rates amongst females in particular. If protective equipment in cricket can be improved, concerns of injury and health may be somewhat mitigated, and there is potential to decrease the number of players leaving the sport for these reasons.

2.2 Cricket ball impact mechanism

The bat-and-ball game involves a hard ball with a diameter of 72mm (Pardiwala *et al.*, 2017), which is bowled over a distance of 20.12m down the pitch towards the batsman

(MCC, 2019). The Marylebone Cricket Club (MCC), which outlines the official laws of cricket followed by Cricket Australia, details that the ball used in men's cricket must weigh between 156g and 163g, while the women's cricket ball ranges between 140g to 151g, and the junior cricket ball falls in the 133g to 144g range (MCC, 2019). The cricket ball consists of a dense, cork and rubber core, contained in an outer layer of leather covering with a central seam (Carré *et al.*, 2004; Cheng, 2008).

Sridharan *et al.* (2015) and Walker (2014) reported ball delivery velocities ranging from 20m/s (72km/h), up to 44.8m/s (161km/h) at a competitive international level. Portus *et al.* (2000) studied the performance of a group of bowlers throughout eight overs, concluding that the average ball velocity was 32.1m/s. Based on the kinetic energy equation for a 163g ball, this is equivalent to a maximum kinetic energy of 163.6J, and an average kinetic energy of 84.0J. Rebound ball speeds off the cricket bat range from 82% to 90% of the delivery speed (Sridharan *et al.*, 2015), or even higher depending on the impact location on the bat (Peploe *et al.*, 2018).

The angle at which the ball strikes the body affects the force that is transmitted. As this inbound angle approaches 90°, the normal component of impact velocity increases, resulting into a greater transfer of momentum and therefore higher contact force (Sridharan *et al.*, 2015). For ball impacts with more rigid surfaces, the elastic deformation of the ball has also been quantified by Carré *et al.* (2004) to be between 1.8mm and 2.7mm. This testing showed hysteresis in the cricket ball response, indicating a degree of energy dissipated by the ball during the impact event. Once the ball impacts the protective pad worn by the cricket player, its kinetic energy is partially absorbed or dispersed by the padding. The post-impact velocity of the cricket ball has been studied by Sridharan *et al.* (2015) in terms of the coefficient of restitution (COR), which is the ratio of rebound to inbound velocity. A low COR indicates a more inelastic material that causes a greater reduction in ball velocity, compared to a high COR. Considering the game play of cricket, a low COR can be somewhat advantageous so that the rebound of the ball is not easily caught by a fielder (Stretch, 2006).

Normal impact testing by Carré *et al.* (2004), also found that the cricket ball is axisymmetric due to its rolled core construction, and the presence of the seam, therefore behaving differently depending on its orientation during impact (Figure 2).

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Figure 2: Differences in force-deflection behaviour due to ball seam. Reproduced from Carré et al. *(2004).*

This was corroborated by a study from Walker (2014), where the seam caused the ball to rebound differently and introduced inaccuracies in the data (Figure 3). This compressive testing showed that the hockey ball, which is very similar to the cricket ball in diameter and mass, produced much more consistent results.

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Figure 3: Inaccuracies due to presence of seam on cricket ball. Reproduced from Walker (2014).

2.3 Injury types and rates of occurrence

With the steady growth in participation and gain in popularity of the more competitive and aggressive T20 game format, it is unsurprising that there is an increasing occurrence of injuries reported overall, both during training and in matches (Pardiwala *et al.*, 2017). Injury is typically defined in literature as an event that exceeds a player's acceptable pain threshold, resulting in distraction from the game. In other cases, injury has been defined as an event that causes a player to be removed from the game, with severity being measured by time spent inactive as a result. The rate of occurrence is particularly high for a non-contact sport (Soomro *et al.*, 2018), with cricket being amongst the top five sources of injuries presented to emergency departments in Australia; this is 7.3% of all sports-related injuries in players over 15 years old (Philipoff *et al.*, 2015).

A proportion of these injuries are due to strains, tears or inflammation associated with strenuous overuse with repetitive motions, overexertion or falls. This is the main injury type for players over 50 years old (Walker *et al.*, 2010a), and can be prevented by different targeted training and conditioning approaches (Shafi, 2014). For players under 50 years of age, Walker *et al.* (2010a) found that contact injuries are much more common; this is defined as injury due to impact from the ball, bat, another player, or the boundary (Shafi, 2014; Pardiwala *et al.*, 2017).

A common injury concern with insufficient protective padding is soft tissue contusions (or bruising) due to blood leakage in the extracellular space following localised blood vessel damage (Walker, 2014). Blood vessel damage mostly results from compression of muscles against bone, which is more likely in the shin or forearm, where there is less soft tissue overlying the bone. Contusions typically impair focus and performance, and severity depends on the location of injury as well as the player's age and fitness (Hrysomallis, 2009; Walker, 2014). In more severe impact events, the high-speed hard cricket ball introduces significant risk of serious injury, with around 60% of cricket injuries involving fractures due to being struck by the ball (Philipoff *et al.*, 2015) and even fatal consequences in other instances (Soomro *et al.*, 2018).

A previous team doctor from Cricket Australia identified 174 trauma-related deaths in both organised and informal cricket over 152 years of play (Brukner *et al.*, 2018). Although fatalities have decreased notably since helmets were introduced during the 1980s, recent deaths have resulted from trauma to the chest and neck. The historical review from Brukner *et al.* (2018) attracted significant media attention, prompting an escalated public desire for protective measures following the death of Australian batsman Phillip Hughes in 2014 (Keane, 2018; SBS News, 2018). Aside from head trauma, the most common cause of death in cricket was found to be a direct blow to the heart region of the chest (Brukner *et al.*, 2018), which can disrupt heart rhythms (known as commotio cordis) and result in cardiac arrest (Doerer *et al.*, 2007). Blows to back of the neck below the helmet can also be fatal, as shown in the case of Hughes and many others, causing haemorrhage at the vertebral artery (Brukner *et al.*, 2018).

According to Shafi (2014), upper limb injuries account for 25% to 32% of cricket injuries, and Philipoff *et al.* (2015) found that lower limb injuries are even more prevalent, accounting for 30% to 50% of injuries. Note that this does not distinguish between injuries due to strain or impact. However, it is known that batsmen are most vulnerable to impact trauma, accounting for 45 of the 174 deaths recorded by Brukner *et al.* (2018), followed by fielders and wicket-keepers. Pardiwala *et al.* (2017) also reported that batsmen endure 86% of craniofacial injuries in professional international cricket. Batsmen and fielders are also at higher risk of injuries to the fingers, such as fractures, dislocations, contusions and sprains (Shafi, 2014), which contribute to 35.4% of recorded upper limb injuries in cricket (Pardiwala *et al.*, 2017).

It must be noted that injuries are defined and categorised differently across studies, such as by the type of injury, location of injury, or player's age group. It is therefore difficult to explicitly distinguish impact injuries from other injury modalities, and thus a comparison between the incidence of impact injuries at different body locations cannot be made based on the current literature. The inconsistencies in cricket injury reporting was identified as a problem by Orchard *et al.* (2005), who devised a universal injury definition and surveillance method. However, some classifications are not detailed enough for the purpose of protection evaluation, and there have been limited reviews of injury available since this method was established to draw significant conclusions.

In general, sports injuries are quite common and may lead to complicated and expensive treatments. Furthermore, treatment can be time-consuming and prevents the player from returning to the field for weeks or months (Pardiwala *et al.*, 2017), which can also impair the team's performance overall. In rarer, more extreme cases, impact injuries are fatal and lead to tragedies that question the safety and public perception of the sport. Protective equipment, particularly for batsmen in cricket, is therefore an obvious area to target for improvement (Sridharan *et al.*, 2015), and it is reasonable, from both medical and economical perspectives, that there is a strong desire for more effective protection from collisions.

2.4 Protective equipment worn in cricket

2.4.1 Rules and regulations

Cricket Australia is a member of the International Cricket Council (ICC), which is the global governing body that administrates the rules and regulations for a cricket game, based on the MCC Laws of Cricket. According to the ICC playing conditions (ICC, 2019b), the official definition of clothing is inclusive of non-visible items worn beneath clothing for protection. This form of protection can be used by any player, whether batting or fielding, and may include body padding such as neck protectors, chest protectors, groin guards and thigh guards. Contrastingly, the ICC (2019b) defines external protective equipment as visible items of apparel, and places specific restrictions on the use of this external equipment during match play. Of the fielders, the wicket-keeper is the only player that can wear gloves and external leg guards (referred to as wicket-keeping pads), unless the umpire gives consent for additional hand or finger protection. However, helmets can be worn by all fielders, as well as the batsmen. If a helmet is worn, it must satisfy the requirements of the British standard, BS 7928:2013. The batsman is allowed to wear external leg guard (referred to as batting pads), batting gloves, and forearm guards (ICC, 2019b).

Despite the potential for severe or even fatal injuries following blows from the ball, helmets and protective gear are not actually mandatory in international cricket. The use of helmets, however, has been recently mandated by Cricket Australia policies, which requires that BS 7928:2013 compliant helmets are worn by wicket-keepers, batsmen, and in-close fielders at all times during match play in all junior and senior community cricket (Cricket Australia, 2018). This will be effective as of the start of the 2019-2020 cricket season. As quoted by Brukner *et al.* (2018), ‘helmets were the most importance piece of protective equipment to be developed’, and this new policy is indicative of a mentality shift with more focus being placed on the importance of protective equipment despite its discomfort, in light of recent fatalities. Pads, gloves and protectors are also recommended, while extra safety equipment, such as neck protectors and the wicket-keeper’s mouth guard, are optional depending on personal preference or the match conditions (Cricket Australia, 2018).

2.4.2 Typical structure and materials used in protective guards

Protective guards serve to reduce the incidence and severity of injury, as well as protect a fragile or recently injured area from further damage from accidental impact. This is done by absorbing incoming energy so that the forces transmitted to soft tissue are minimised, and dispersing the force received over a greater area (Dlugosch *et al.*, 2012). Padding is attached to different locations of the body, usually by means of Velcro straps tightly fitted to the body curvature or in the form of inserts. In terms of groin and upper leg protection, various inserts can be secured in batting shorts, which are preferred by many players as they do not feel as restrictive or apply as much uncomfortable pressure as separate sets of straps would (Cricketers Hub, 2019).

The high density foams used in protective padding must be somewhat flexible, and are usually made from polymers such as polyethylene (PE), ethylene-vinyl acetate (EVA), and polyurethane (Stretch, 2006; Bartlett *et al.*, 2010; Sridharan *et al.*, 2015). During the impact event, the foam absorbs energy through deformation and therefore dampens the impact by increasing the collision contact time, and reducing the maximum transmitted force through the body (Laing and Carr, 2005). The outer shell of the protective padding has a critical role in load spreading. It is made of a more rigid, high-strength material such as polycarbonate, which is lightweight and resistant to tears and impacts (Sridharan *et al.*, 2015). This shell must have sufficient stiffness to avoid permanent damage to the protective equipment, while dispersing the load over a greater area.

Protective padding can exhibit vastly different responses under impact due to structural differences in their composition. Walker (2014) studied the composition of leg guards with traditional cane construction, as well as more modern leg guards with high density polymer foams. Both types generally incorporate longitudinal rolls that allow the guard to conform around the player's leg, with each roll containing one cane or one segmented piece of foam. Deformations across three brands were found to be between 45mm to 75mm, over contact times of 7ms to 12ms (Walker, 2014). Using a finite element model of a cricket ball impacting a polycarbonate-EVA sandwich, Sridharan *et al.* (2015) studied the material response of a typical protective pad, finding that the optimal combination of layers involved thicknesses of 4mm, 8mm, and 3mm respectively. With a ball impact speed of 45m/s, this material model absorbed 7.2J/kg, resulting in a transmitted force of 3.54kN and a maximum stress of 0.464MPa on the skin, which is well below its ultimate tensile strength. This research gives an indication of the range of values that could be expected during experimental testing.

2.4.3 Compromise between protection and comfort

The design goal for protective equipment is to absorb impact energy such that the level of damage caused in the area being protected is eliminated, or reduced to an acceptable level (Laing and Carr, 2005). This is typically done by means of an outer rigid shell, and an inner foam padding or lining, in order to achieve shock absorption and pressure distribution in response to sudden forces of impact (Dlugosch *et al.*, 2012). However, the thickness and conformity of the layers used for protection compromises the wearer's comfort and freedom of movement, which can detract from their sporting performance. This may be a reason why many players choose not to wear protective pads at all, and risk injury from ball impact instead.

The overall study of literature in this area found that the current review of protective equipment in cricket covers the efficacy of equipment, and its satisfaction of basic safety requirements, but there was little focus on user comfort before notable research by Stretch (2006) and Webster (2010). In a review of padding performance, Stretch (2006) found that in most cases, the equipment is sufficient for protection and meets legal requirements but does not meet the comfort requirements of the wearer, and herein lies an opportunity for future improvement. When investigating the key factors that determine the level of comfort and performance that a leg guard achieves from an athlete's perspective, Dlugosch *et al.* (2012) found that sensorial comfort, thermal comfort, weight, protection, aesthetics, and, above all, fit, were most influential. This aligns with findings from Webster (2010), which emphasised that the fit of the leg guard was the most important factor to ensure that the guards did not feel restrictive or apply uncomfortable levels of pressure to the athlete's leg. In terms of thermal comfort, padding can be uncomfortable over long periods of time, resulting in significantly increased skin temperature and fluid loss, and therefore an additional physiological strain on the body (Stretch, 2006). The equipment weight can lower efficiency of movement, with Webster (2010) reporting decreased running speeds while wearing leg guards, compared to without.

2.5 Evaluation of cricket protective equipment performance

The research available on the performance of protective equipment has focused heavily on helmets and leg guards, such as wicket-keeping pads or batting pads. This is likely because these pieces of equipment are most strongly recommended to players, and are used consistently in match play compared to other optional or additional pads. There is strong evidence supporting the efficacy of helmets since they were adopted in 1978, with Pardiwala *et al.* (2017) reporting a decreased rate of head and facial injuries from 62% to 4%, and Brukner *et al.* (2018) emphasising the significant role of helmets in reducing cricket fatalities. Although certain aspects still require further improvements, such as protection against concussion and vulnerable open areas at the grill, head protection is not the focus of this project, and so leg guards will be studied more closely to draw parallels with padding used in other areas of the body. Although not extensive, there has also been some literature found to assess the efficacy of chest protectors, which is presented below. However, research into forearm protection has been extremely limited, and so a review cannot be presented here. The reason for this may be that many players do not actually use forearm guards during play, and as such, no studies have been found to specifically evaluate the effectiveness of arm guards in preventing forearm injuries.

2.5.1 Leg guards

Traditionally, the overall trend identified was a strong correlation between pad thickness and a reduction in peak transmitted force (Hrysomallis, 1996; Bartlett *et al.*, 2010; Sridharan *et al.*, 2015). However, with the development of more thin and lightweight materials in protective padding development, Hrysomallis (2009) found that similar levels of protection were provided for different brands of padding with varying masses and thicknesses (Table 1).

Table 1: Impact force attenuation of cricket thigh pads under consecutive drop tests. Reproduced from Hrysomallis (2009).

Table has been removed due to copyright restrictions.

Another factor to consider is the negative impact that raised temperature and humidity levels have on the padding's ability to absorb energy, based on data from Hrysomallis (1996) that identified six out of eleven pads failing to meet safety requirements under these conditions. This effect is not considered in the British standard of safety testing but may be significant under realistic playing conditions, depending on the climate.

Severe injuries to the lower limbs while wearing protection have not been widely reported in literature. This either suggests a lack of review, particularly considering the difficulties in distinguishing impact injuries to other types of injuries, or indicates that batting pads are performing adequately in preventing these injuries.

2.5.2 Chest protectors

Further analysis was presented by Doerer *et al.* (2007), who looked into protection against potentially fatal direct blows to the chest. According to Brukner *et al.* (2018), chest protectors are not yet commonly worn by cricketers, aside from elite level athletes who seek protection against ribcage fracture and bruising. However, with chest blows being one of the leading causes of death in cricket after head trauma, it appears that current levels of protection are insufficient. Doerer *et al.* (2007) reviewed the most popular chest protectors commercially available to find that most focused on protection from traumatic structural injury, but did not offer complete protection from arrhythmia. Furthermore, Doerer *et al.* (2007) observed that in almost 40% of fatal commotio cordis cases across various sports (such as football, baseball, lacrosse and ice hockey), players were wearing equipment marketed to protect against traumatic chest injury. These failed chest protectors all consisted of a polymer foam inner layer, and a fabric or shell outer layer. These results indicate a clear need for improvements in chest protection to reduce the risk of commotio cordis for cricket players.

2.5.3 Official testing standard BS 6183-3:2000

The effectiveness of protective equipment against impact in cricket is currently evaluated against British standards, set by the British Standards Institution in 2000 (Laing and Carr, 2005). In particular, helmets must satisfy BS 7928:2013 to be worn in international cricket matches, as well as organised community games in Australia (Cricket Australia, 2018). For the purpose of testing protective pads to be used at other locations on the body, the relevant standard is BS 6183-3:2000, which covers leg protectors for batsmen, wicket-keepers and fielders, as well as thigh, arm and chest protectors for batsmen (British Standards Institution, 2000; Laing and Carr, 2005; Bartlett *et al.*, 2010).

This standard deems that the necessary level of protection is dependent on the skill and strength level of the opposition. Protectors are assessed by zones of protection, which divide the guard or pad into different areas of protection. For example, the chest protector is divided in the outer area (Zone 1) and the heart area (Zone 2). Due to copyright restrictions, specific metrics and diagrams cannot be reproduced here from the standard. However, the main points that are relevant to this study include the energy levels applied in testing, the maximum allowable transmitted forces, and the setup of the apparatus used. Depending on the performance level required for the guard and the location of impact on the guard, the standard impact energies to be used in testing range from 5J to 40J (British Standards Institution, 2000). The maximum transmitted force for the guard to be deemed adequate ranges from 4kN to 6kN (British Standards Institution, 2000). These values are selected based on the force required to cause tibia fracture (Bartlett *et al.*, 2010).

The standard impact test for protective guards involves attaching the protective pad (via straps or similar) to a steel anvil mounted onto a load cell, and impacting the pad in a series of drop tests with a steel hemispherical striker. The frequency response of the load cell must be at least 10kHz, allowing a continuous force measurement to be obtained over time, and the capacity of the system must range up to 50kN (British Standards Institution, 2000). There are four anvils outlined with differing shape and dimensions depending on the body part that the guard is intended to protect. One such anvil has been described by Walker *et al.* (2010b), which is shaped to imitate a leg or forearm (Figure 4). The steel anvil has a length of 350mm and a 25mm diameter curved surface, supported on either end (Walker, 2014). The system must be bolted or clamped down to a concrete or similar base, with a mass of at least 1000kg (British Standards Institution, 2000). The anvils for the thigh and chest are cylindrical, but also have a curved surface on which the guard is secured.

Figure has been removed due to copyright restrictions.

Figure 4: Front view (left) and side view (right) of the anvil used to test leg or forearm cricket guards, drawn according to BS 6183-3:2000. Reproduced from Walker et al. *(2010b).*

The impactor has a 2.5(±0.1)kg mass and 72(±2) mm diameter, and is dropped with a maximum impact velocity of 5.66m/s (British Standards Institution, 2000; Webster, 2010). The drop height is measured from the surface of the protector, and must be adjusted to reach an accuracy of ±5% of the required energy (British Standards Institution, 2000). The test involves five impacts conducted on each zone, with an additional two impacts in visibly weak areas of the guard. The standards also describe a preparation period that precedes drop testing, to simulate the 'wearing in' stages of used pads (Walker, 2014).

Table 2: Summary of testing requirements as outlined in BS 6183-3:2000 (British Standards Institution, 2000)

Parameter	**Requirement**
Impact energy applied	5J – 40J
Maximum impact velocity	5.66m/s
Maximum transmitted force	4kN – 6kN
Minimum rate of sampling system	10kHz
Measurement capacity of system	50kN
Impactor mass	2.5kg
Impactor diameter	72mm

2.5.4 Factors not addressed in BS 6183-3:2000

There are a number of factors associated with the typical impacts received during a cricket match that are not considered in the standard, and therefore areas that are not reflective of the realistic situation. Firstly, the steel hemispherical striker is much harder than the cork and rubber cricket ball. This means that the ball's deformation during the impact event, which is indicative of some energy being absorbed, is not accurately mimicked in the standard testing (Bartlett *et al.*, 2010). The test is based on an equivalent kinetic energy principle, to generate similar energy levels with a different mass and velocity, but Walker (2014) pointed out that the maximum kinetic energy tested according to the standard is 40J, which is well below the levels of impact that are likely involved in a game. Also, the impact velocity of 5.65m/s is nearly ten times less than the speeds experienced in reality. Considering the strain rate dependency in softer type materials like the foams used in padding, Walker (2014) argues that a higher, more realistic velocity should be maintained with a lower impactor mass to better represent the hysteresis in the material response. While this would indeed be more realistic, recreating this high impact velocity has been acknowledged to be difficult in controlled laboratory settings.

Although the transmitted force is limited to 5kN to pass safety requirements, there is no limit on maximum pressure. This assumes that a higher transmitted force corresponds with a higher risk of injury, but some sources suggest that pressure would be a more reliable correlate for injury, particularly in the case of contusions (Bartlett *et al.*, 2010). However, considering the short duration for this type of dynamic impact response, pressure can be difficult to measure and the sampling rate of the measuring device is particularly crucial in ensuring that peak data is not lost. In this sense, force is generally analysed for simplicity and accuracy (Walker, 2014). It is also interesting to note that the peak force that can be transmitted in the standard testing protocol is 5kN to reflect tibia fracture mechanics, which means that less severe injuries such as contusions are not accounted for. While these types of injuries are not fatal, they do have the potential to negatively affect an athlete's concentration and performance during play. That being said, it may be difficult to quantity the level of impact involved in causing contusions, due to a potentially wide spread of variance in tolerance data across different people. It is therefore reasonable that there has not been a definitive criteria in testing to reflect this type of injury due to this uncertainty.

As discussed previously, an evaluation of leg guards from Hrysomallis (1996) found that elevated temperature and humidity also detracted from the pads' protective characteristics, which is also not addressed in the standard. This may be a relevant factor, particularly for games of cricket played in more hot and humid climates. Finally, another key factor that the standard does not address is the characteristic properties of a human limb, which differs greatly from the steel anvil that represents it. A true representation would be termed 'biofidelic', and incorporate the soft tissue response of deformation under impact. There has been little experimental testing using realistic limb models in cricket pad evaluation, although this set up has been explored in other contexts before for other types of impact situations.

Overall, it seems that there are many areas that are not realistic in testing the full performance capabilities of leg guards in cricket, according to BS 6183-3:2000. Many specific aspects of performance would require implementation of slight changes to the testing method for a more accurate simulation of impact events. However, the protocol serves as a consistent, repeatable method upon which global comparisons can be made between different guards, and is satisfactory for the purpose of preventing most injury types under normal playing conditions.

2.5.5 Inclusion of soft tissue surrogates in impact testing

The lack of a realistic human surrogate in the standard testing protocol has been reported as a key shortcoming in the assessment of protective equipment (Payne *et al.*, 2015). In most cases, a simple metal anvil is used as a human surrogate, following the BS 6183-3:2000. However this surrogate is inadequate in expressing a realistic human impact response, and therefore does not give an accurate insight into how protective materials would behave in practical use. The use of a more biofidelic surrogate would simulate the behaviour of injured tissue more closely, and is therefore considered a valuable addition to the testing protocol in order to evaluate the risk of injury (Payne *et al.*, 2014).

The artificial surrogates used to assess protective equipment efficacy are either computational, using finite element methods, or synthetic materials, which are ideally inexpensive, for frangible single use, or durable, for repeated testing. Payne *et al.* (2015) reported that greater biofidelity is usually found in frangible surrogates, where the visible damage can be used to indicate potential injury, although experimental trials can be more time-consuming due to constant replacement.

The use of biofidelic soft tissue surrogates in sports impact testing has been very limited, but substituting biological tissue with gelatine is common in military applications. According to Jin *et al.* (2018), the similarity between ballistic impacts in muscle and gelatine are similar and therefore indicates that this substitution is reasonable, provided that the surrogate exhibits consistent responses. Very few studies in sports impact testing have implemented this method, but notable work by Hrysomallis (2009) replicated the response of a cricket thigh pad against a realistic, deformable base by using Silastic 3481. This is a silicone-based surrogate that was found to be consistent and durable, with a reasonably accurate tissue density. The surrogate was selected based on data from human and cadaver material, and incorporated into a model of the thigh by using a stainless steel beam to represent the femur. This work was also addressed by Payne *et al.* in consecutive studies conducted in 2014 and 2015, which found that a blend of a two-part additive cure Polydimethylsiloxane (PDMS) silicone elastomer gave a closer simulation of muscle deformation in cases where the muscle is not contracted during activity or anticipation. However, the PDMS silicone elastomer is not as durable as Silastic 3481 due to its higher stress response (Payne *et al.*, 2014). Overall, the current soft tissue simulants have been found to provide a reasonable gross representation of body tissues as a whole, although the surrogates could be improved by analysing the mechanical behaviours of constituent tissues (Payne *et al.*, 2014).

Ballistics gelatine has long been universally considered as a soft tissue simulant, and is typically mixed in gelatine mass concentrations of 10%, following the Federal Bureau of Investigation (FBI) protocol, or 20%, following the North Atlantic Treaty Organization (NATO) protocol (Jussila, 2004; Clear Ballistics, 2017b). Jussila (2004) reviewed the standardised methods for preparing ballistics gelatine, and found that the production and storage of gelatine must remain consistent for reproducible results. According to Jussila (2004), the preparation of gelatine blocks involves dissolving a calibrated amount of powder (typically 250A bloom type) into warm water in a mould, and adding the necessary preservatives. After firing shots at multiple locations on different gelatine blocks, it was found that there were no significant differences in penetrations, as well as similar responses for batches stored over varying time periods. This indicates that the gelatine blocks are homogenous and consistent, and may therefore be a suitable choice to be implemented in testing.

2.6 Project Significance

2.6.1 Gap in current research and development

The review of literature found that there is currently a heavy emphasis on helmets, particularly surrounding the recent policy changes that mandate the use of helmets in international cricket, as well as focused analysis of leg guards that protect the shin and knee, since these are used consistently by batsmen and wicket-keepers and play a critical role in injury prevention. Comparatively, there has been little attention given to experimental testing or analysis of protective padding for other areas of the body, such as the chest, forearm and thigh. With the inconsistencies in the reporting of injury rates and types, it is difficult to ascertain the current level of protection that is provided by existing chest, forearm and thigh guards.

However, there was convincing evidence from Doerer *et al.* (2007) to suggest that chest protectors require improvement, supported by fatal incidences of commotion cordis reported by Brukner *et al.* (2018). There was also no literature found to distinguish between the level of effectiveness of chest protection for females compared to males, which may be an interesting area of research considering anatomical differences. There has been very little work undertaken to survey or test on female cricket players, although this may increase in future if female participation rates increase. Furthermore, it is evident that forearm impact injuries are still prevalent, particularly amongst batsmen, with reports of Pakistan's Babar Azam being taken off field last year, following a forearm fracture that required at least six weeks to recover (AFP, 2018). In more recent media, Australia's Glenn Maxwell, Shaun Marsh, and Steve Smith were all injured in the forearm after being struck by a cricket ball, with Marsh's more serious injury ruling him out of the World Cup campaign (Cameron, 2019; Giles, 2019; Pugh, 2019). There is a clear need for further research into the design of protective equipment that not only achieves the necessary protection for players of all ages, also provides better comfort and performance in order to be accepted by athletes in a physically demanding sport.

The evaluation of testing protocols currently in place identified many areas that can be improved in order to more closely match realistic playing conditions. While the British standards are appropriate to test protective padding for comparative purposes, material testing that incorporates both the deformation effects of a real cricket ball and the soft tissue response of the body has not been studied extensively.

2.6.2 Project purpose

This project is driven by a client with the aim of exploring the possibilities of protection using patented Isoblox technology. This is a thin, hexagonal mesh layer that provides impact dispersion properties, which has been successfully coupled with foam layers in the past for head protection in baseball. The purpose of this project is to evaluate the effectiveness of the Isoblox material and find the optimal combination of materials to integrate with this technology. This can be used to develop a novel protective guard that is appropriate for the levels of impact received in cricket, and can be used comfortably by players of all ages and skill levels. The client has a desire to develop protective guards that can be used for the forearm, thigh and chest. In particular, the client has indicated a concern for the lack of protection for breast tissue in female players, based on experience in the sporting field. The long-term significance of the experimental testing that will be undertaken in this project is the development of more effective protective materials that can be used not only on the cricket field, but also in other impact sports and applications in the future.

Chapter 3. Methods

3.1 Replicating cricket ball impact in an experimental setting

The kinetic energies experienced in a competitive cricket game were replicated as potential energy implemented in the drop tower. As described by Equation 1, the kinetic energy KE is dependent on the object's mass m and velocity v. Potential energy PE, as described in Equation 2, is a product of the object's mass m, gravity g and fall height h.

$$KE = \frac{1}{2}mv^2 \quad (1)$$

$$PE = mgh \quad (2)$$

This energy equivalence is depicted below (Figure 5).

(a) (b)

Figure 5: (a) Kinetic energy of cricket ball. Adapted from Scott (2015). (b) Potential energy implemented in drop tower.

Balls delivered by elite fast bowlers have reported speeds ranging from 32.4m/s to 44.8m/s (Wormgoor *et al.*, 2010; Walker, 2014; Sridharan *et al.*, 2015). Note that this is the ball release speed, which would be greater than the impact speed received by the batsman. The mass of a cricket ball ranges between 140g to 151g for women's cricket, or 156g to 163g for men's cricket. The maximum cricket ball mass of 163g was selected for calculations to account for the 'worst-case' scenario, as it would give the highest kinetic energy (Table 3).

Table 3: Kinetic energies correlating with the range of velocities reported for fast bowlers

Speed category	Velocity		Energy (J)
	(m/s)	(km/h)	
Lower limit	32.4	116.64	85.56
Upper limit	44.8	161.28	163.57

Therefore, the aim was to replicate the energy levels in the range of 85.56J-163.57J with the drop tower. The apparatus to be used in the impact testing was limited to a maximum height of 0.64m, from the base plate on which the sample would be placed, to the bottom of the impactor. Note that the thickness of the sample would also detract from the fall height and therefore have a small effect on the potential energy produced. Based on this drop height, Equation 2 was used to gauge the masses needed to replicate the above energy levels in Table 3.

For a height of 0.64m, the mass required to produce the maximum 163.57J of energy would be 26.05kg. This was not feasible as the laboratory masses totalled to only 25kg altogether. Furthermore, repetitive manual lifting of 26.05kg throughout the testing phase would pose an occupational health and safety risk, with concerns of potential strain to the muscles in the shoulder and arm with overuse.

The client was therefore consulted about lowering the energy to be reproduced in testing. This was important to ensure that he was still satisfied that the testing protocol would still give meaningful results, which could be accurately translated into a real cricket game situation. Based on this discussion, the client set the target energy value to 130J, which would be significant enough to replicate the majority of fast bowl speeds in competitive cricket. For a set height of 0.64m, this requires a mass of 20.7kg instead.

However, preliminary testing at lower energy levels found that at a mass of 11.3kg, some materials were experiencing peak forces of over 14kN. The load cell implemented in the testing system had a capacity of 20kN. With consideration towards the safety of the equipment, it was decided that testing would be performed using a lower mass of 11.3kg, rather than 20.7kg. This mass was also much more manageable in terms of manual lifting, and did not pose a significant safety risk to the operator.

The final parameters selected for testing in the drop tower are listed in Table 4. Note that due to the changing thicknesses of material samples, the drop height changes slightly between samples. Consequently, this causes minor changes in the potential energy applied to the sample, as well as the equivalent velocity that the energy represents. These parameters were used consistently for all samples, except for the 10mm gelatine layers which were tested at a lower mass of 3.77kg (generating 23.3J of energy).

Table 4: Experimental testing parameters

Parameter	**Value**
Height (m)	0.60 – 0.62
Mass (kg)	11.30
Energy (J)	66.21 – 68.73
Equivalent in-game velocity (m/s) (km/h)	28.50 – 29.04 102.60 – 104.54

3.2 Modifications to drop tower apparatus

A drop tower had been previously designed at Flinders University by Neilsen (2016), for the purpose of assembling the head-neck taper junction in hip prostheses by emulating a surgeon’s strike to the femoral head. The drop tower uses ball bearing rails to enable a linear fall of a mallet attached to a load cell (Figure 6). The apparatus consists of passivated mild steel and aluminium parts, and utilises a Kelba Miniature Compression Cell to measure loads of up to a capacity of 20kN (Kelba, 2018). The product information for this load cell is detailed under the model name of KPAMNC 2000 (Appendix A). There were three major changes made to the original apparatus, in order to make the equipment more compatible with this project.

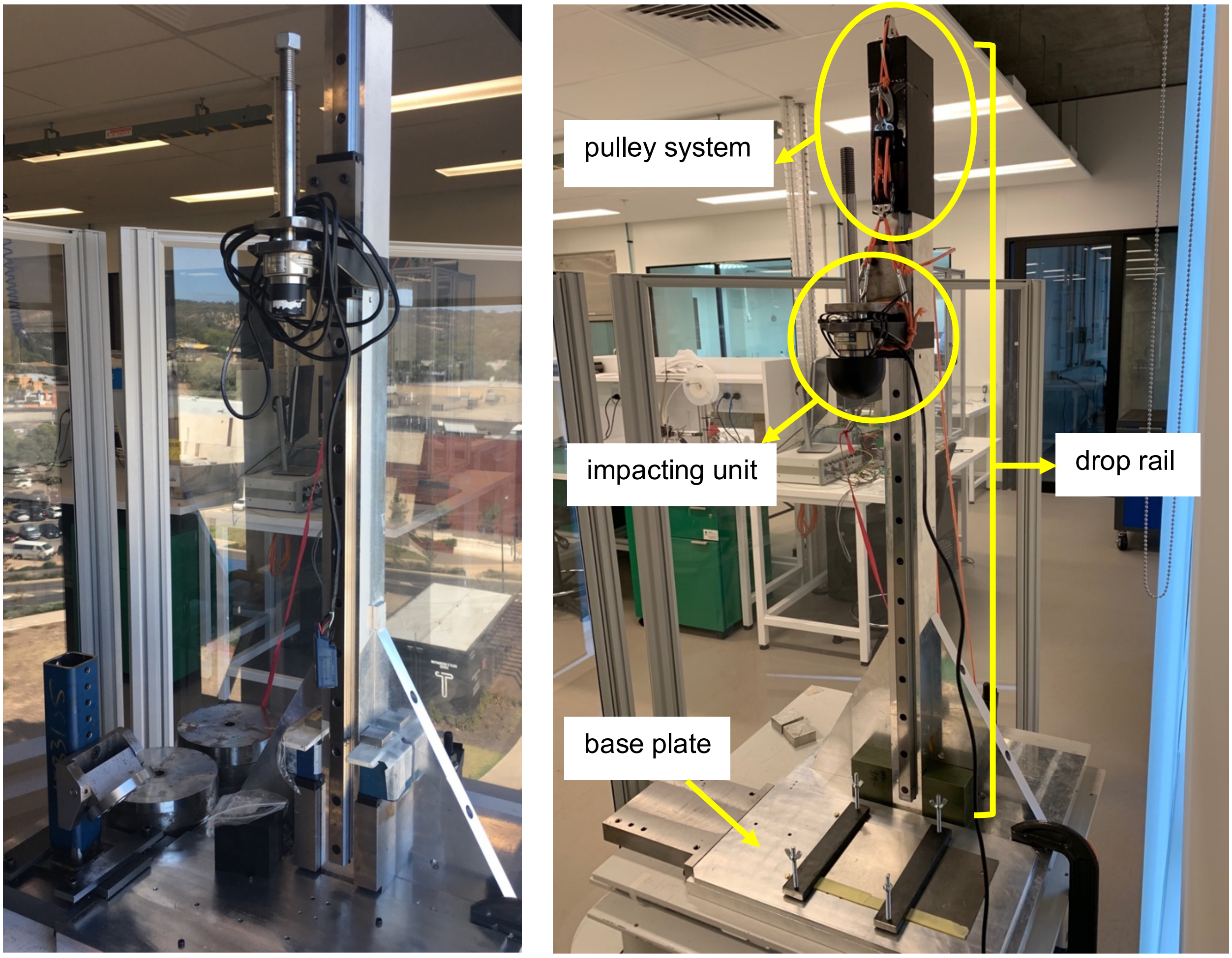


Figure 6: Original (left) and modified (right) drop tower apparatus

3.2.1 Pulley system to lift impacting unit

A pulley system was incorporated into the drop tower apparatus by another final year biomedical engineering student for a more efficient method of lifting the impacting unit during cyclic testing (Figure 7). In the system designed by Belder (2019), the black sheath slides over the top of the drop rail and uses a pulley on top to redirect the marine braided rope, allowing it to be pulled from behind. The 316 stainless steel hook connects to a system of four pulleys, which reduces the amount of work input needed to lift the impacting unit.

The only slight modification made to this system was the addition of two 5mm zinc plated steel snap hooks with a safe working load of 100lbs (45.36kg) each, purchased from a hardware store. This allowed the pulley system to be disconnected from the impacting unit before each drop, to eliminate any frictional resistance that the pulleys would contribute to the drop. Incorporating two hooks allowed for the rope to be released easily from either side, even when larger masses were loaded onto the rod.

Figure 7: Pulley system designed by Belder (2019)

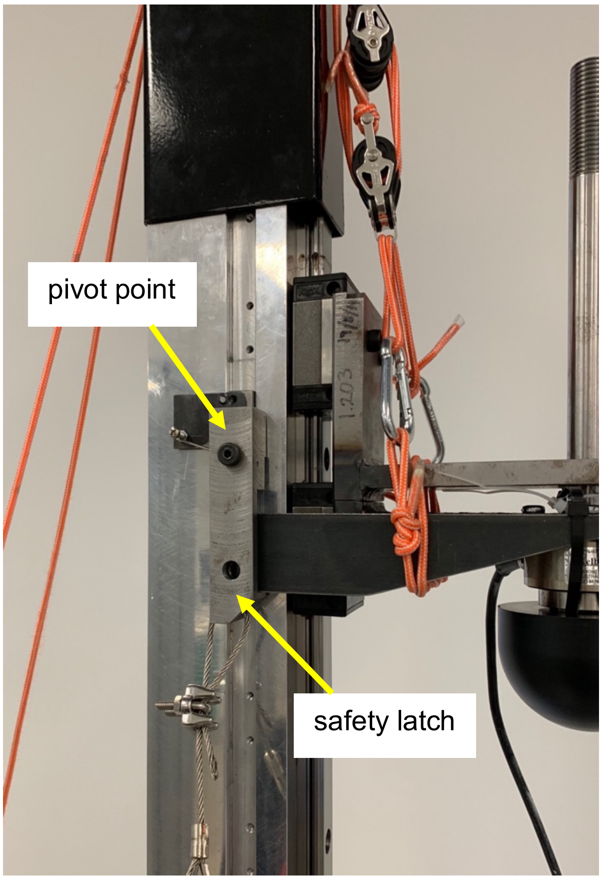


Figure 8: Drop height limited by pulley system

The disadvantage of this system was that it limited the maximum height that the impacting unit could be fixed to. The safety latch is a spring-loaded mechanism that pivots about a screw and releases the impacting unit down the drop rail when pulled in a clockwise direction (Figure 8). The screw is fixed into one of the existing holes along the drop rail, meaning that the height settings are predetermined and cannot be fine-tuned. The system cannot be lifted further once the top and base pulleys come into contact, which dictated the chosen height setting. Measuring from the lowest point of the impactor to the base plate on which the samples are positioned, the maximum allowable drop height in this case was 0.64m.

Despite the reduced drop height, this pulley system is particularly advantageous for the greater energy levels, and therefore heavier masses, required in this application. The use of the pulleys provided ease in the lifting process, which minimised the risk of muscle strain for the operator. Furthermore, the pulley system increased efficiency, allowing more drops to be completed compared to the alternative of unloading and loading masses to enable safe manual lifting between drops.

3.2.2 Impactor design and material selection

A new impactor was designed to closely resemble a cricket ball, with a hemispherical head and diameter of 72mm (Appendix B.1). The final product implemented in the drop tower was attached to an existing adaptor piece via four screws and fixed onto the load cell by press fit (Figure 9). This press fit connection became worn with use, most likely due to the friction between the load cell and the adaptor piece during each drop. Due to the loosening of this attachment, cable ties were added to secure the impactor to the unit (Figure 9). This ensured that there was minimal movement of the impactor against the load cell during testing, which would have contributed to noise in the load cell output data.

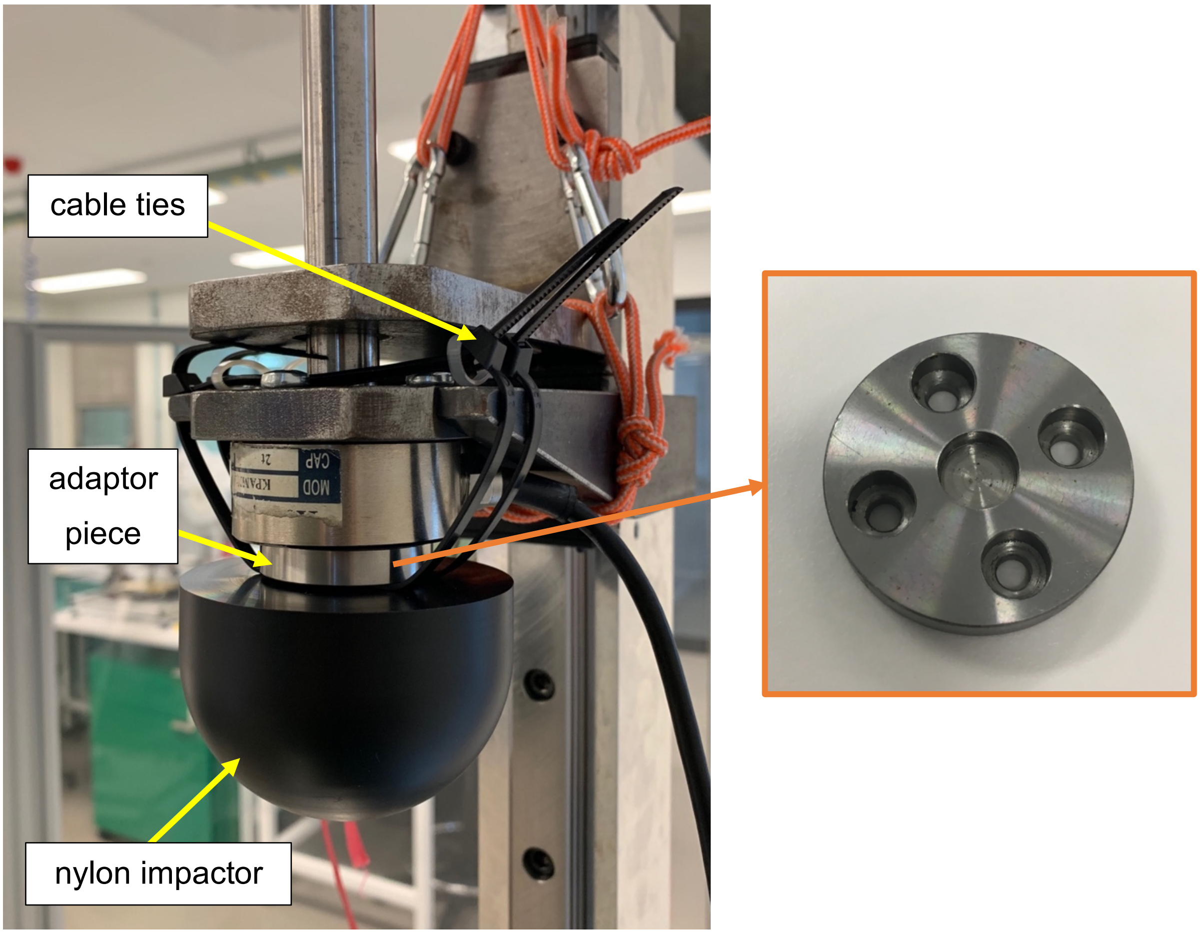


Figure 9: Nylon hemispherical impactor fixed onto sliding unit in drop tower

While an actual cricket ball would have been a more realistic impactor, its rolled core construction and the presence of the seam result in axisymmetric properties. The cricket ball is also cased in an outer layer of leather, which wears in with use and therefore changes its properties over time. Using a cricket ball as the impactor would have therefore introduced inconsistencies in testing, which may have affected the resulting data. The testing standard BS 6183-3:2000 uses a steel hemispherical impactor, which is reliable in terms of material consistency throughout impact testing. However, a steel component of this size would be too heavy for the press fit connection to hold.

The impactor was therefore manufactured from nylon, which was considered a suitable material due to its low density and smooth finish. Furthermore, the client had previously used nylon to simulate a cricket ball in a machine to ‘knock in’ (precondition) new cricket bats. In this application, nylon proved to be effective and long-lasting.

3.2.3 Sample fixture on drop tower base plate

The size of the material samples to be tested was limited by the base plate area available, and by the dimensions of the ballistics gelatine block to be used in testing. The gelatine block was 16 inches (40.64cm) in length, with a square cross section of 6 inches (15.24cm) in width and height. With initial plans to cut out cross-sectional slices of gelatine, the samples were cut to match these dimensions. Based on this, the base fixture (Figure 10) was designed to be compatible with 6 inch square samples.

The system uses four points of fixation with threaded holes added to the existing base plate (Appendix B.2). The two mild steel plates (Appendix B.3) were then placed on top of the sample and the wing nuts were lightly fastened to prevent the layers from displacing during the impact event. The wing nuts were not turned further after coming into contact with the steel plates, to prevent the fixture from applying a clamping pressure down onto the sample. This pressure would potentially impose an undesirable boundary condition near the impact region and affect the response of the gelatine and materials.

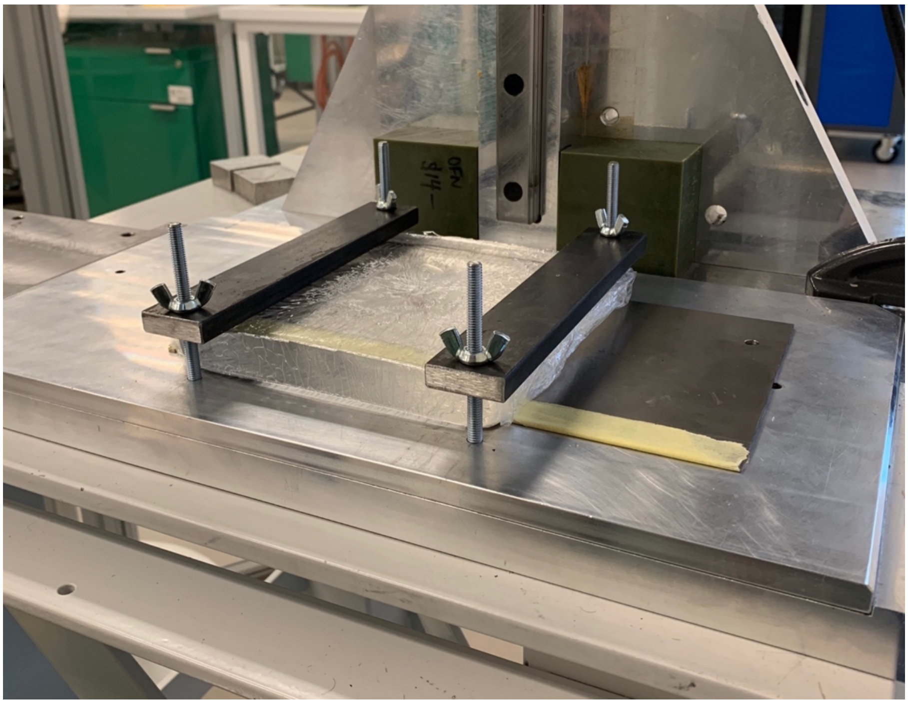


Figure 10: Fixation of gelatine sample on flat metal sheet with wing nut fasteners

A flat, 3mm thick metal sheet was placed on the base plate, under the gelatine sample. This was necessary to cover the exposed pre-existing holes in the base plate from past experiments (Figure 11). The edges of these small holes punctured the base of the gelatine layer during impact, causing premature damage to the materials (Figure 12).

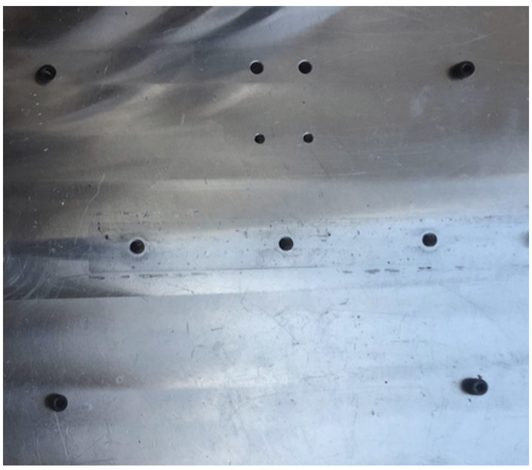


Figure 11: Exposed holes in drop tower base plate

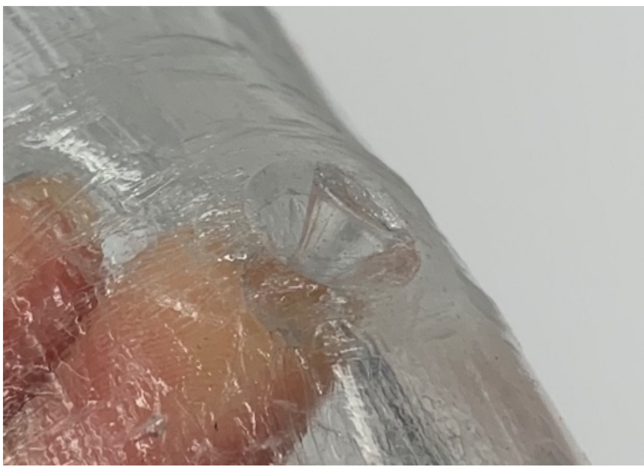


Figure 12: Punctured gelatine from pre-existing base plate holes

3.3 Preparation of samples

3.3.1 Ballistics gelatine as a soft tissue simulant

As discussed in the literature review (Section 2.5.5), ballistics gelatine has been used extensively in the past to model human soft tissue, although its application in the sports impact testing field has been limited. The use of ballistics gelatine in the impact testing set up for this project deviates from the standard BS 6183-3:2000 procedure, which tests the protector against a steel anvil. However, including a layer of gelatine provides a more realistic simulation of the impact event occurring on a cricket protective pad against a limb. This enables a more fidelic response of the protective materials as they are able to flex and deform as they would on a human limb. Furthermore, the gelatine increases the impact duration and therefore lowers the peak force, which is a safety measure in protecting the sensor from being over-loaded. Since all testing done in this project is comparative, having the gelatine base is ideal.

The ballistics gelatine used in this project was sourced from Clear Ballistics through a local supplier. This is a 10% concentration gelatine that is transparent, synthetic, odourless and stable at room temperature (Clear Ballistics, 2017a). The gelatine is made following the FBI standards. Based on the material safety data sheet (MSDS) (Appendix C), the gelatine is an advantageous choice for use in the laboratory, as its non-hazardous and non-toxic properties allows for easy handling and storage (Clear Ballistics, 2017b). The advantage of using this ballistics gelatine is that it is pre-mixed and therefore more time efficient, easily accessible, and has been well documented in literature for other applications. The block of gelatine obtained (Figure 13) measures 40.64cm in length, and 15.24cm in width and height, with a mass of 8.16kg.

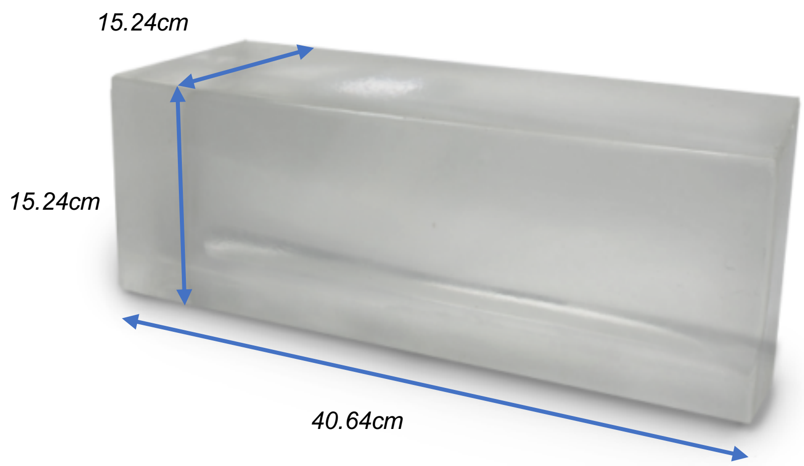


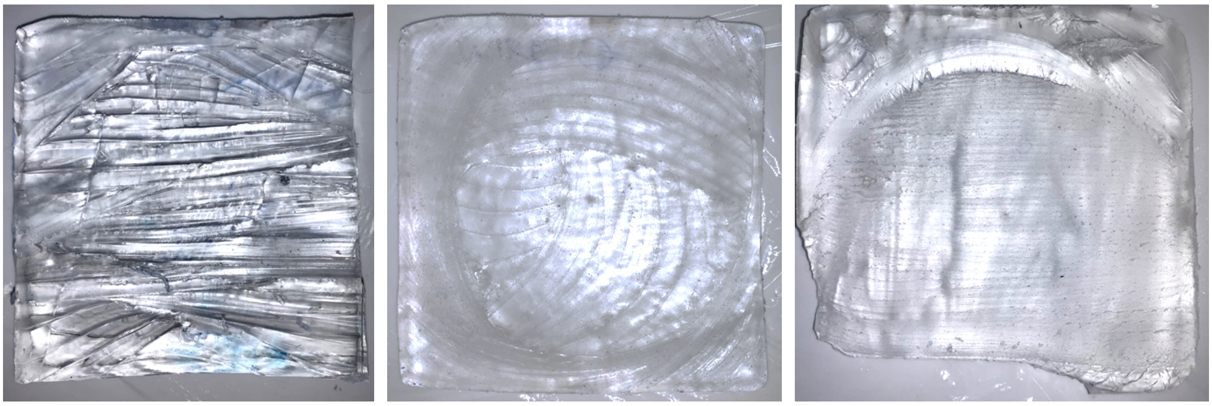
Figure 13: 10% ballistics gelatine block. Adapted from (Clear Ballistics, 2017)

The locations of interest on the body for protection are the upper leg, forearm and chest. Of these areas, the forearm has the smallest thickness of soft tissue overlying bone and is therefore more vulnerable to fracture injuries. To account for the 'worst-case' scenario, this was the basis of the gelatine thickness to be used in testing. The thickness of soft tissue in the forearm is quite variable depending on factors such as gender, age, nutrition, muscle mass, whether the arm is tensed or at rest, and where the measurement is taken (Iivarinen, 2014). However, the average thicknesses of soft tissue layers have been reported Iivarinen *et al.* (2011), using the dominant forearm of nine healthy adult male and female subjects (Table 5). These measurements were taken with the arm at rest, from the mid ulna region (in the proximal-distal direction) on the dorsal side, between the ulna and radius bones (Iivarinen, 2014). For simplicity, this was rounded to 10mm as a target thickness for the ballistics gelatine layer. Note that after preliminary testing, the thickness was increased to 20mm (as explained later in this section).

Table 5: Thickness of soft tissue layers in forearm at rest (Iivarinen et al., 2011)

Soft tissue component	**Thickness (mm)**
Skin	2.1
Subcutaneous adipose tissue	2.1
Muscle	10.3
Total	**14.5**

Challenges were met when cutting the gelatine block into 10mm thick slices. Multiple attempts with cutting tools including knives, wires, scalpels, and hacksaws showed that it was very difficult to obtain a smooth, even surface by manual cutting. The application of pressure to the gelatine block during cutting and each pull of the blade or wire caused the material to deform substantially, leading to uneven cuts (Figure 14). This was problematic, as the surfaces ridges introduced inconsistencies in the gelatine thickness throughout one sample. Furthermore, this method did not allow for accurate repeatability across different gelatine layers.



(a) *(b)* *(c)*

Figure 14: Uneven gelatine slices obtained by cutting by (a) knife, (b) wire, and (c) hacksaw

Re-melting the gelatine into a mould was therefore the chosen method to prepare the gelatine slices, as it proved to be much easier and produced uniform, smooth slices of consistent thickness. The re-melting process was considered reliable, as it is commonly used to reform gelatine blocks for future use while retaining material properties. The procedure was adapted from the supplier's re-melting instructions (Appendix D), which details the steps needed to melt an entire gelatine block into its original form.

To resize the gelatine into the desired thickness, a 20cm carving knife used to cut out a small, manageable quantity of gelatine, which was then teared up into smaller pieces in the mould (Figure 15a). Gloves were used for this process to avoid contamination of the material from any debris or foreign substances on the hands. A 15.24cm square mould was used to match the original dimensions of the gelatine (and therefore the fixtures designed to hold the samples). The desired mass of gelatine was calculated based on the material density and desired thickness and measured using a set of scales (Figure 15b).

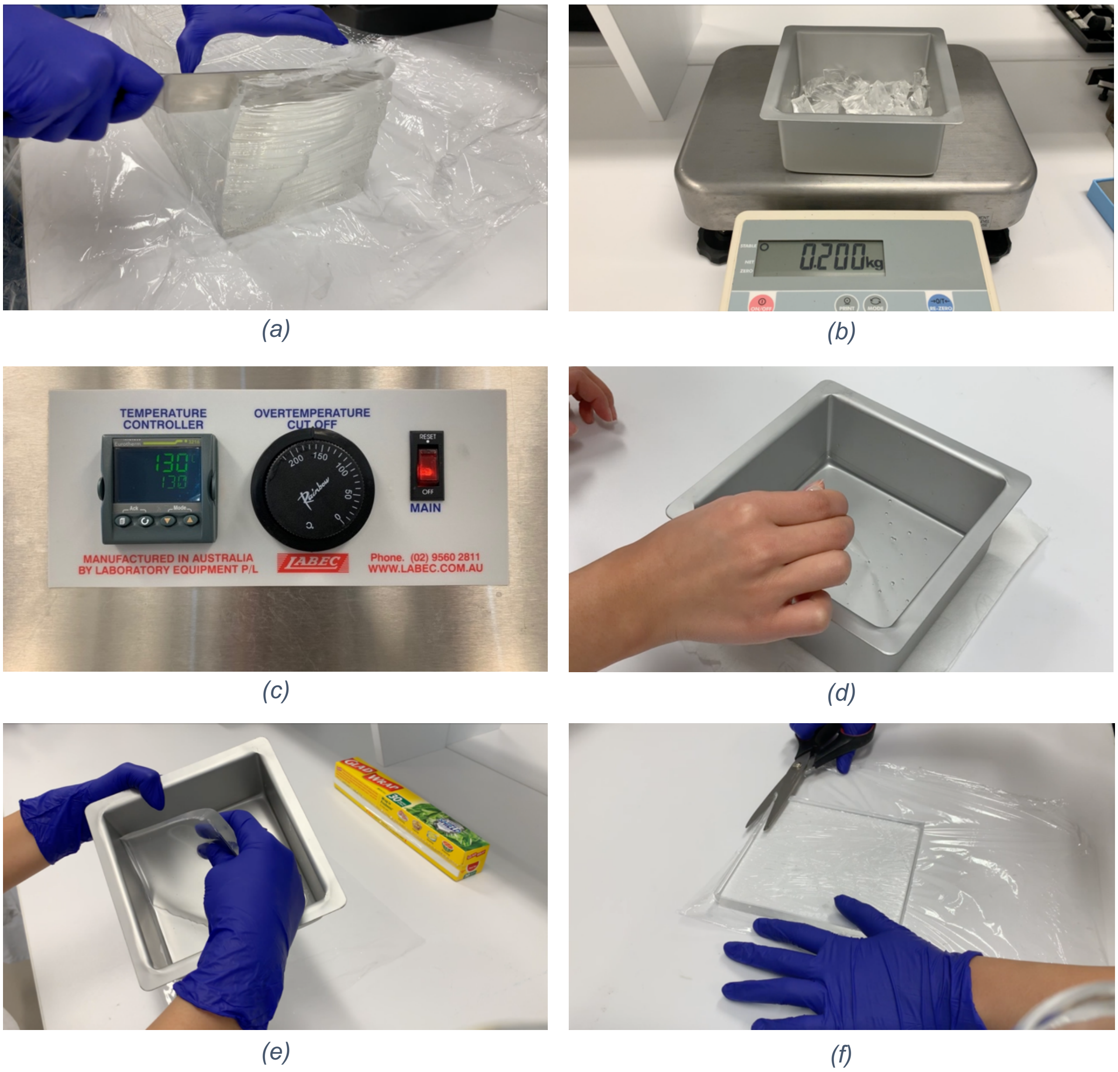


Figure 15: Process of re-melting ballistics gelatine to desired size involving (a) cutting a rough portion from the gelatine block, (b) measuring the desired mass into a mould, (c) melting the gelatine in the oven for one hour at 130°C, (d) release surface bubbles using a pipette, (e) removing the sample from the mould after cooling for one hour, and (f) trimming the edges to remove the meniscus.

According to the MSDS, the gelatine has a specific gravity of 0.91 (H_20=1) (Clear Ballistics, 2017b). Specific gravity can be defined using Equation 3 below:

$$SG = \frac{\rho_{gelatine}}{\rho_{H_2O}} \tag{3}$$

This gives a gelatine density of $\rho_{gelatine} = 910kg/m^3$. For a 10mm thick layer in a 15.24cm mould, the desired volume is:

$$\begin{aligned} V &= l \times w \times h \\ &= (0.1524)^2 \times 0.010 \\ &= 0.000232\ m^3 \end{aligned}$$

Applying Equation 4:

$$\rho = \frac{m}{V} \tag{4}$$

This gives a required gelatine mass of 211g in order to produce a 10mm thick layer. This mass was then doubled to produce a 20mm thick layer in later stages of testing.

The sample was then melted in the laboratory oven for one hour at 130°C and removed using fire-resistant heat safety gloves. This melting process resulted in bubbles rising to the surface of the melted gelatine, which were then removed gently with a clean pipette (Figure 15d). After cooling for one hour, the gelatine layer was slowly pulled out of the mould, and the edges were trimmed to remove the meniscus. The sample was loosely wrapped in cling wrap to avoid contamination with foreign substances. Overall, this process ensured a constant thickness across different samples, with a smooth and consistent surface for the materials to be placed on. Furthermore, this re-melting process could be repeated multiple times and the gelatine could therefore be re-used to make new samples throughout testing. This was particularly important, as it was found that the gelatine was damaged after one drop and therefore could not be used with multiple samples.

As mentioned previously, the gelatine thickness was changed from 10mm to 20mm after preliminary testing. These drop tests on the isolated 10mm gelatine layers were conducted at a height of 0.63m and mass of 3.77kg, which provided 23.3J of energy. It was expected that the peak forces would be reasonably consistent, considering the homogeneity of the material and the identical preparation method. However, it was apparent that the peak forces measured were extremely varied, with some samples producing less than 1000N of force and others producing over 5000N (Appendix E). It was concluded that the duration of the impact event was likely extremely fast, given that the gelatine was unprotected, and was therefore not reliably captured by the software. Comparing the data captured at 2kHz and 5kHz, the difference in trends indicate that the sampling rate has a notable effect on the peak force recorded from these 10mm gelatine samples. It is likely that the sampling rate, even set at 5kHz, is simply insufficient to capture the exact point at which the peak force occurred. Since greater thicknesses provide increased protection, and therefore a lower peak force with an increased contact time, the gelatine layer thickness was changed to 20mm for testing. This thickness is still relevant as a representative soft tissue layer in the context of providing protection to breast tissue for women, and the upper leg.

3.3.2 Selection of protective foam and Isoblox layers

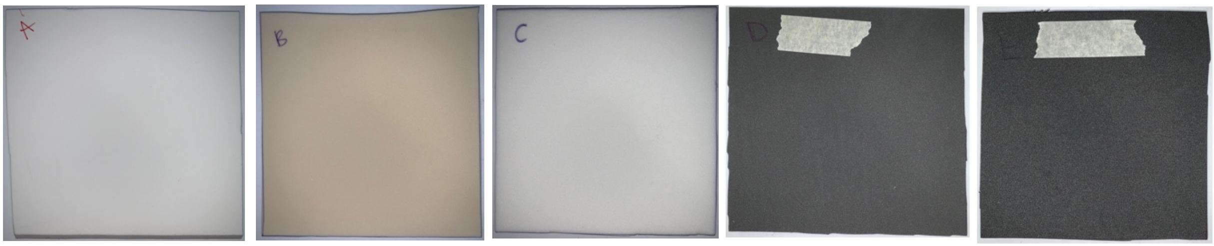


Figure 16: Five foam types A-E (left to right)

Five different foams were provided by the client for testing, and labelled A-E for reference (Figure 16). These foams are variations of closed cell cross-linked copolymers, EVA and PE, with different densities and thicknesses (Table 6). Foam A is of particular interest to the client, as it is thin and flexible, making it ideal for the innermost layer of protection that is positioned next to the skin. Foam C is particularly soft and lightweight, while Foams D and E are much stiffer. Foam D was the foam tested with Isoblox by Ziegler (2016) in the prototype found to be superior to reputable competing brands.

Table 6: Specifications of five different foams to be tested

Label	Material	Density (kg/m^3)	Thickness (mm)
A	EVA	220	3
B	PE	90	7
C	EVA	45	10
D	PE	140	6
E	PE	120	10

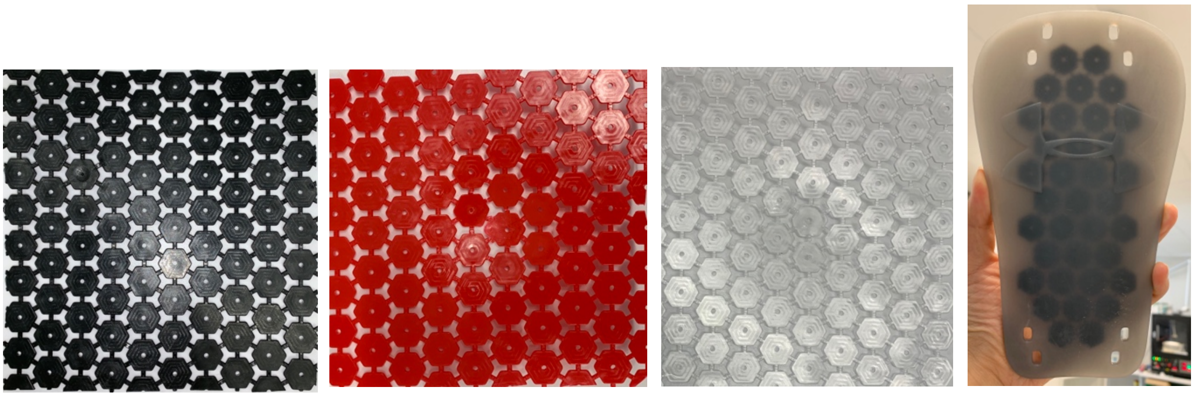


Figure 17: Four Isoblox compositions X, R, T and Z (left to right)

In addition to the original Isoblox material, three new compositions of Isoblox were also provided towards the later stages of the project for evaluation. These have been distinguished by colour (Figure 17), with details listed below (Table 7). Note that the black Isoblox embedded in gel (Isoblox Z) was moulded with a curvature and is therefore non-uniform in thickness throughout the sample. It was also more difficult to make observations about the Isoblox integrity on this sample after testing, as the gel was not completely transparent.

Table 7: Specifications of four different compositions of Isoblox to be tested

Label	Material Description	Thickness (mm)
X	Black Isoblox (original)	1.75
R	Red Isoblox	1.75
T	Transparent Isoblox	1.75
Z	Black Isoblox embedded in gel	4.0-12.0

The foam and Isoblox layers were cut to match the dimensions of the gelatine layer (15.24cm x 15.24cm). Foams B, D and E were cut using a knife, whereas the more flexible foams, A and C, were cut using scissors. The Isoblox materials were cut using hand pruners with carbon steel blades, purchased from a local hardware store. Isoblox Z was not cut and therefore did not match the standard dimensions of other sample layers. All layers in the samples tested were layered with the configuration, so that observations of damage could be linked to the peak force data.

The testing protocol initially considered the following variables:

- Foam type (A, B, C, D, or E)
- Number of foam layers (1-2)
- Number of Isoblox layers (1-4)
- Relative position of Isoblox sheets (staggered or aligned)
- Lay-up order

The following boundaries were set according to the client requirements:

- Maximum thickness = 30mm
- Inner layer must be foam
- Outer layer must be Isoblox

Considering all combinations of these variables, given the above conditions, it was found that a total of 1530 drop tests would be required for a full factorial analysis. This included three drops per configuration, but did not include drop tests needed to establish single layer material characteristics, calibration drops, drops at different energy levels, and testing on competing brands. This number of tests was not feasible in the given project timeline, nor was it an efficient approach to take.

A fractional factorial analysis was considered for the experimental design, following the Taguchi Methods (National Institute of Standards and Technology, 2012), in order to maximise the results obtained from a smaller number of tests. This involves studying the main effects and interactions between different factors, and drawing inferences about combinations that were omitted from testing. However, it was found that the analysis was complicated given the number of levels and variables involved. This type of analysis also did not account for specific client requirements.

The client was therefore consulted to identify the key variables of interest to prioritise and remove any unnecessary testing. This consultation resulted in a heavily reduced testing matrix of 318 drops (inclusive of three drops per configuration), after eliminating combinations that were considered to be not commercially viable. The amount of testing was reduced again after preliminary testing, where unexpected findings showed that samples were being permanently damaged after one drop and therefore could not be re-used throughout testing. The force transmitted through some configurations approached the limit of the load cell, and therefore testing of these samples could not continue. Furthermore, the amount of visible damage to some samples immediately ruled out particular combinations, since they were deemed inadequate for protection.

Based on this, the results of this thesis assess the performance of all five foams, all four Isoblox compositions, as well as a select number of configurations involving Foam A and Isoblox X. This was done by creating one sample for each configuration and performing five successive drops on each sample. The materials that performed best were then re-tested another two times for repeatability, and optimal combinations were then produced and tested based on these trends. For all samples containing more than one Isoblox layers, the sheets were positioned with all plates and hinges aligned (as opposed to staggered). A full list of combinations tested is given in Appendix F.

3.4 Data collection and processing

3.4.1 Data acquisition set up

The load cell was connected to a National Instruments (NI) CompactDAQ USB chassis, cDAQ-9178 (National Instruments, 2019a), and the output was recorded in the NI SignalExpress software (National Instruments, 2019b).

Figure 18: cDAQ-9178 compact USB chassis

The software provided options of filtering and resampling the input data, as well as other manipulation processes such as zeroing and averaging inputs. Since the variable of interest was the peak force, the filtering and resampling processes were removed as they would potentially remove or modify this desired peak data point. Instead, zeroed raw data was collected, which was more advantageous in giving an accurate peak force value, and allowed for filtering or manipulation in the post-processing stage if necessary. A sampling rate of 5kHz was set in the NI SignalExpress software, following guidance from the engineering services department to obtain the maximum frequency that was appropriate for the load cell specifications, without introducing excessive noise into the measurement.

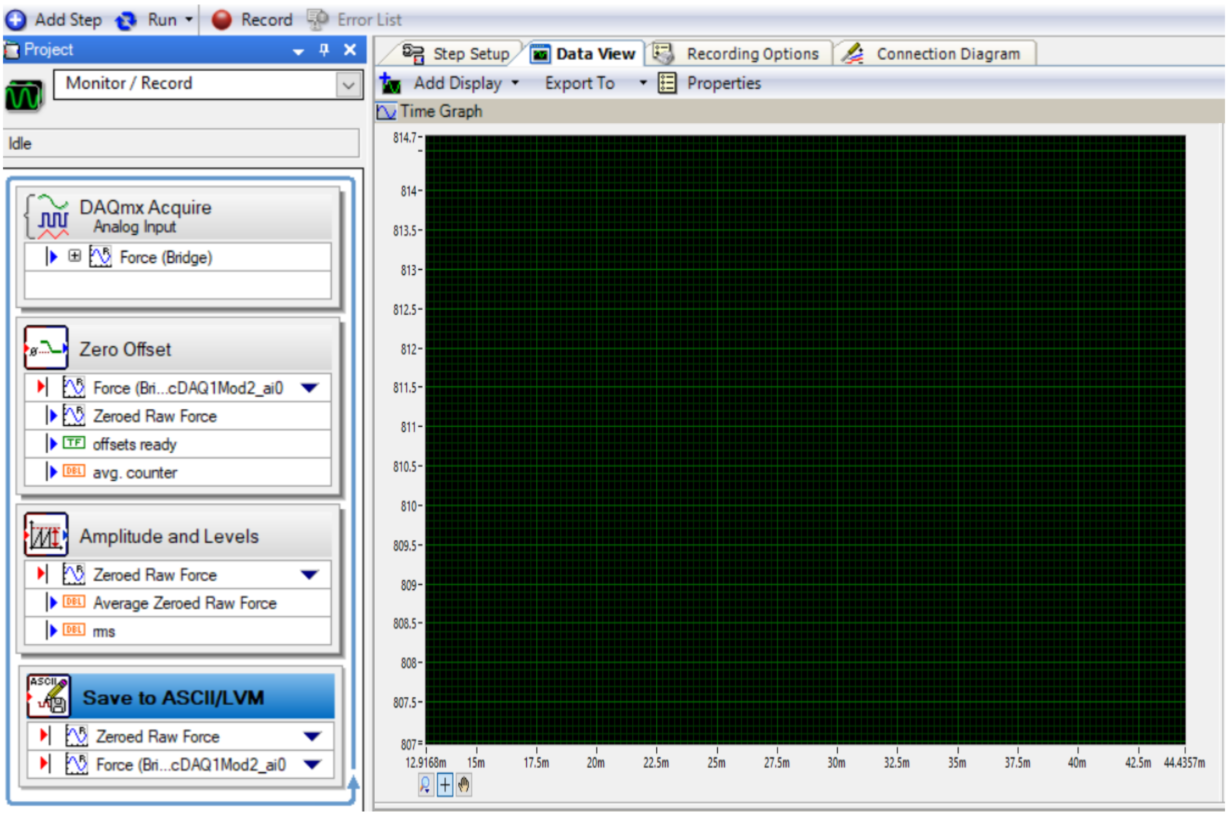


Figure 19: NI SignalExpress project used to capture load cell data

The data view tab (Figure 19) showed the real-time force amplitudes being recorded, while the step setup tab allowed the properties of each project process to be changed. The force recording was zeroed before each drop in the 'Zero Offset' process, and the file names were updated each time in the 'Save to ASCII/LVM' process. The save settings (Figure 20) exported the results as a comma separated value (CSV) file containing the time markings in the first column, and the force data in the second column. This is determined by the order of inputs selected in the 'Signals' tab.

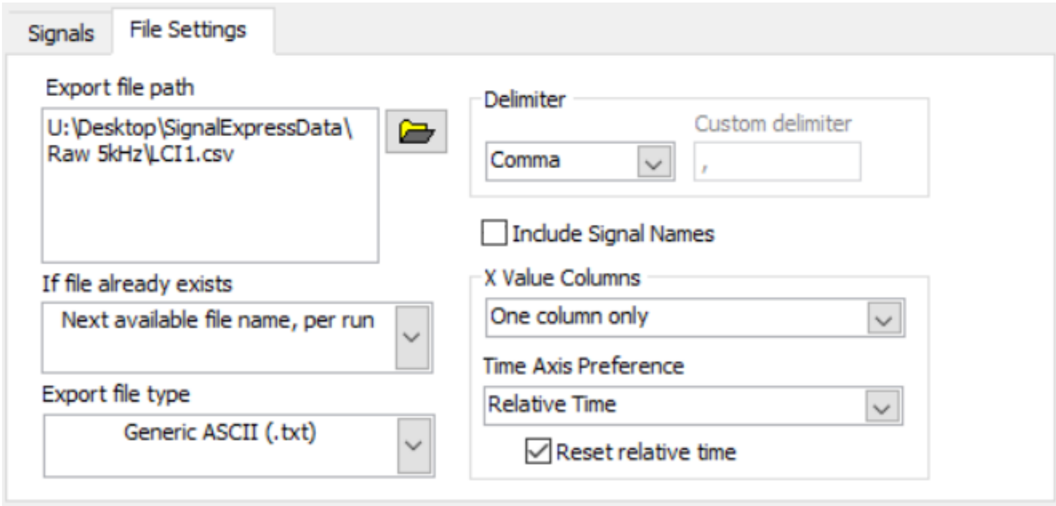


Figure 20: NI SignalExpress data file save settings

3.4.2 Drop testing procedure

At the start of each testing session, a load cell integrity test was performed to ensure that the load cell was recording accurately, and also to precondition the cell gauges. These tests were particularly important during higher energy impact tests resulting in high loads transmitted through the system, to ensure that there was no damage to the cell. The test consisted of three cycles of loading and unloading all available masses, one at a time, onto the impacting unit, which rested on a solid block of material on the tower's base plate. In this static set up, the theoretical force was calculated by Newton's second law of motion (Equation 5), based on a gravitational acceleration of $g = 9.81ms^{-2}$ and the mass applied to the unit.

$$F = ma \tag{5}$$

For the total mass of 25kg, a force of 245.25N was expected. In most cases, the force reading was slightly elevated, by less than 5% of the theoretical value. This was considered a minor error that is negligible since all testing is done on a comparative basis, and this error is consistent for all integrity tests. After each of the three loading and unloading cycles, the sensor was zeroed.

To perform the drop tests, masses were loaded onto the rod attached to the impacting unit, totalling to 11.30kg (Figure 21). The masses of all individual parts used in the impacting unit are detailed in Appendix G for future reference.

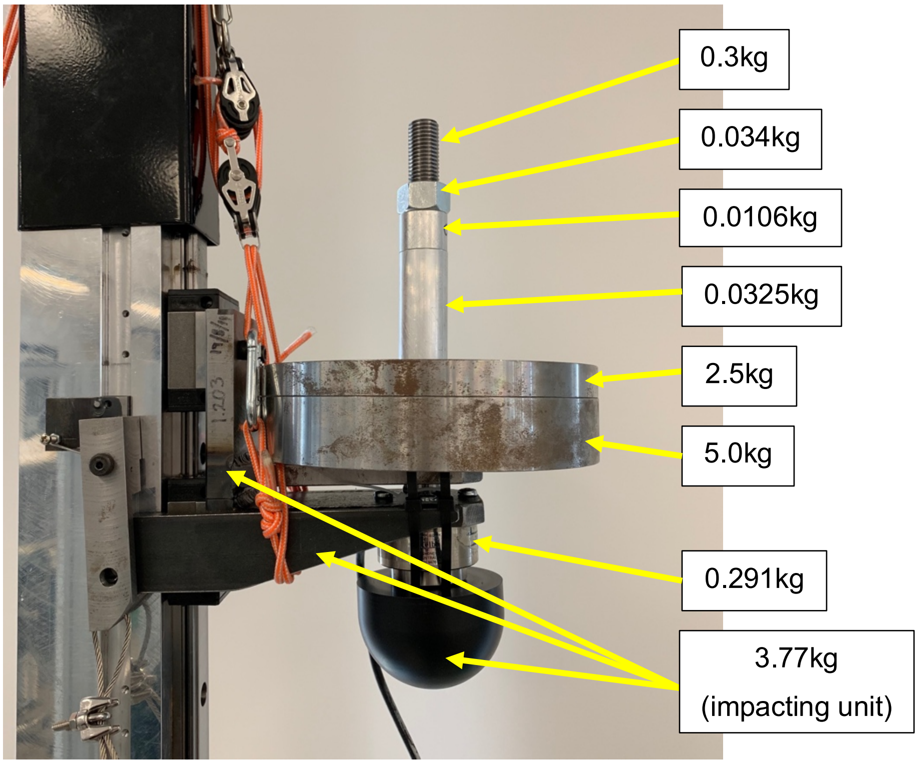


Figure 21: Masses added to impacting unit result in a total drop mass of 11.30kg

The carabiners were connected in order to lift the unit to the safety latch, at a drop height of 0.64m above the base plate. All stoppers were then removed from the base, and the sample was placed in the fixture, along with a layer of gelatine. The hooks were then detached from the unit and positioned out of the way. The load cell was then zeroed, and then data file name was updated to include the lay-up configuration (listed from bottom to top), the sample number, and the drop number. The 'Run' button was then clicked to start recording, and the safety release cable was pulled to trigger the drop of the impacting unit onto the sample. After all bounces, the recording was stopped. This process was repeated five times per sample.

3.4.3 Data analysis on MATLAB

The resulting CSV files were imported to MATLAB (MathWorks, 2019) using the *DataProcessor_ReadIn.m* script (Appendix H.1). This program was written to save the relevant force and time data to a structure, along with useful information such as the material name, drop number, number of layers in the material sample, and the peak force. Four different bar graphs were then produced, comparing the peak forces for different gel samples, foams, Isoblox compositions and lay-up configurations respectively. For the optimal materials that were tested three times, the median and range values for each successive drop were also calculated and provided as an output. These steps were done using the *DataProcessor_Plot.m* script (Appendix H.2). Another script, *DataProcessor_ForceTime.m*, was also written to plot the force vs. time profile of preliminary tests, with the time scale being manipulated to align the peak force with time zero (Appendix H.3).

Chapter 4. Results

The samples tested were named according to the following labelling key, with all samples starting with a 20mm layer of gelatine, G. The names refer to the materials in the sample, listed from bottom to top, with the number of letters equalling the number of layers. For example, sample GAX refers to a layer of gelatine, Foam A and Isoblox X (Figure 22).

G	gelatine (20mm thickness, unless otherwise indicated)
X	original Isoblox (black)
R	new Isoblox (red)
T	new Isoblox (transparent)
Z	original Isoblox embedded in gel
A-E	foam type

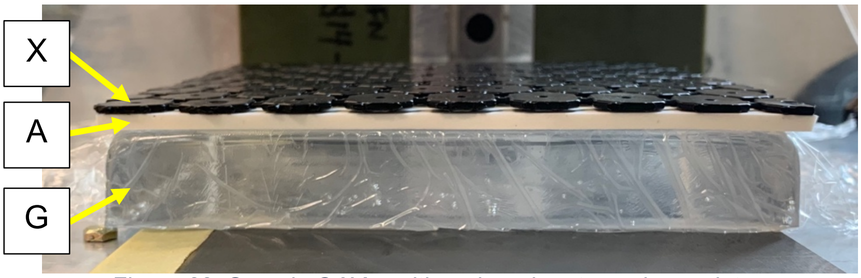


Figure 22: Sample GAX positioned on drop tower base plate

The results focus on a comparison of peak forces between different samples, represented visually using bar graphs. A full list of tabulated peak force values for all samples tested can be found in Appendix I.

4.1 Force vs. time profile

The force and time data obtained from the drop tests typically followed a profile with multiple peaks observed as the impactor bounces on the sample (Figure 23). The peak force (labelled) is taken as the maximum point of the first bounce.

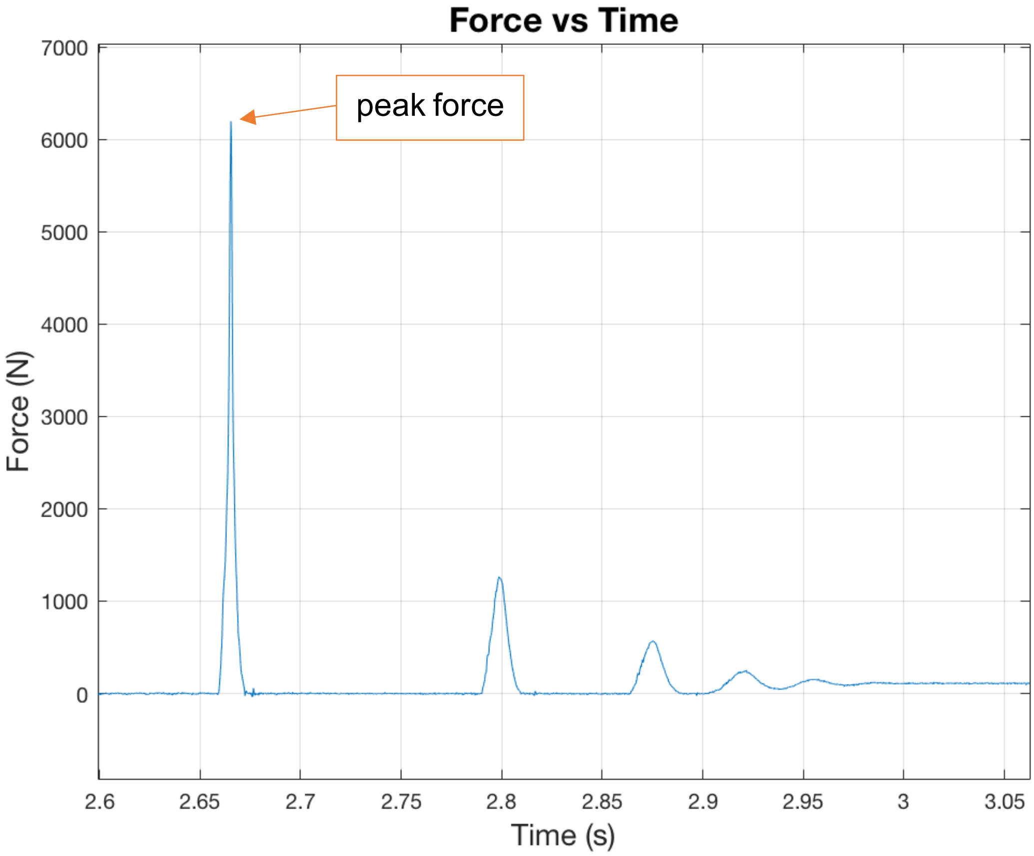


Figure 23: Example of typical force vs. time profile

4.2 Layer configurations for Foam A and Isoblox X

Samples GA and GX produced peak forces of 17639N and 13323N respectively (Figure 24), and the single layer of both materials experienced considerable damage after one drop (Figure 25). Sample GA in particular produced a high peak force which approached the load cell capacity, and was completely punctured at the central impact point. Consequently, successive drops were not tested, and further testing of other single layer materials was not continued. Instead, the results from samples GA and GX are used as a benchmark reference for comparison with other configurations.

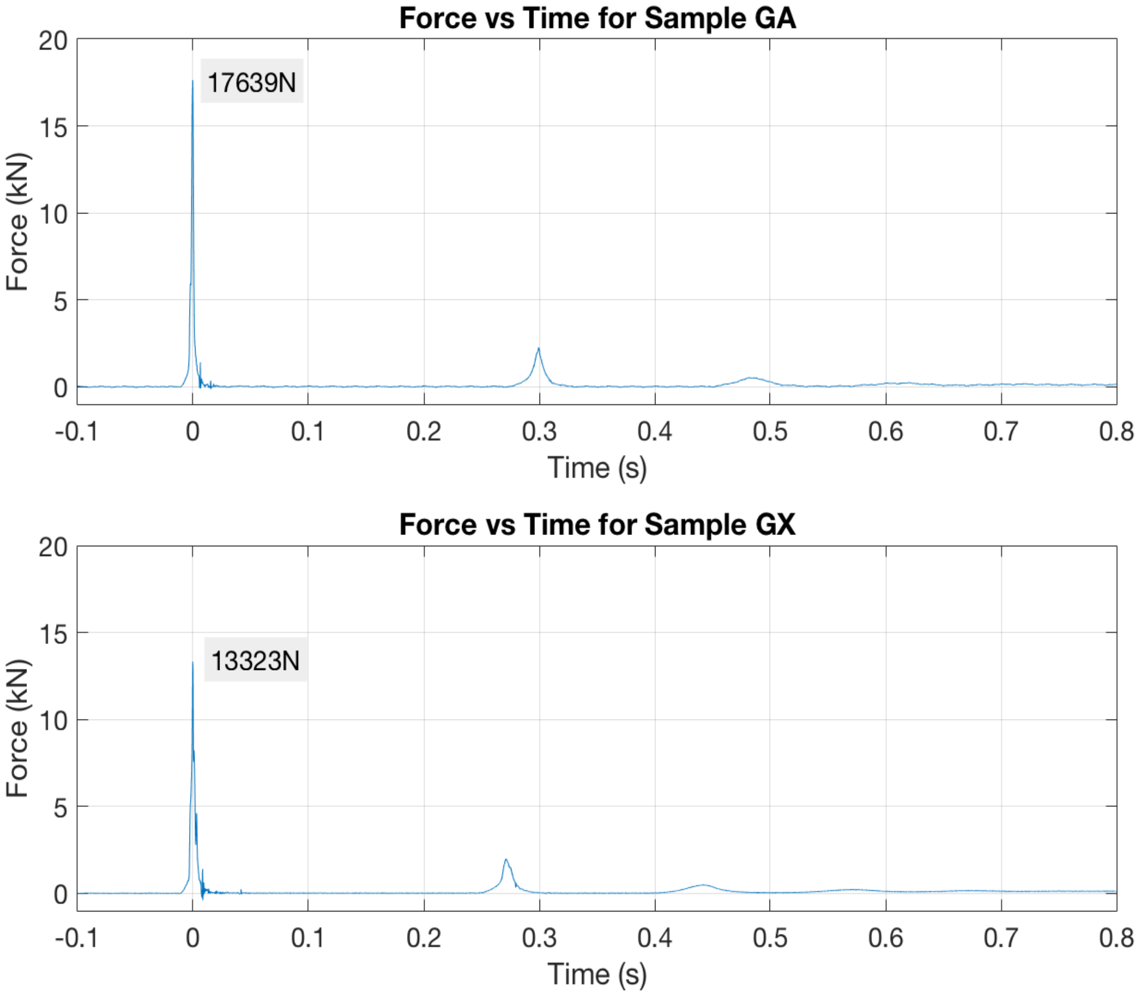


Figure 24: Force vs. time profiles for samples GA and GX, showing high peak forces approaching load cell capacity

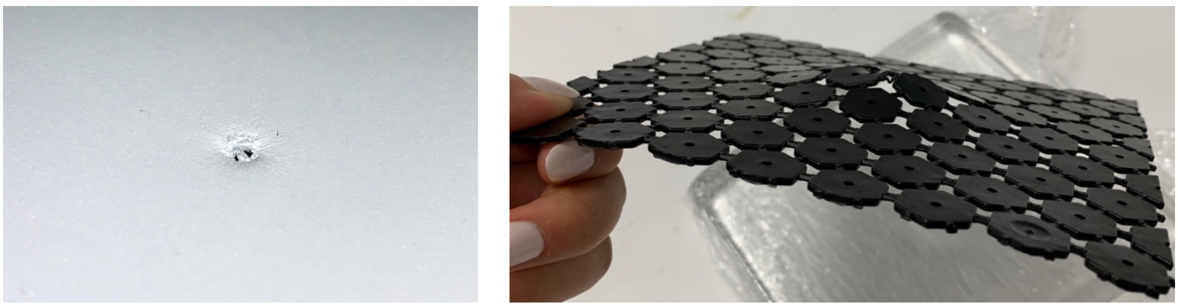


Figure 25: Permanent damage to samples GA (left) and GX (right) after one drop

The client had a particular interest in setting Foam A and Isoblox X as the base materials to be positioned against the limb (or gelatine layer). The following configurations therefore start with layers GAX, with different combinations layered on top of this base. Configurations of two to five layers were assessed to compare the resulting peak forces (Figure 26).

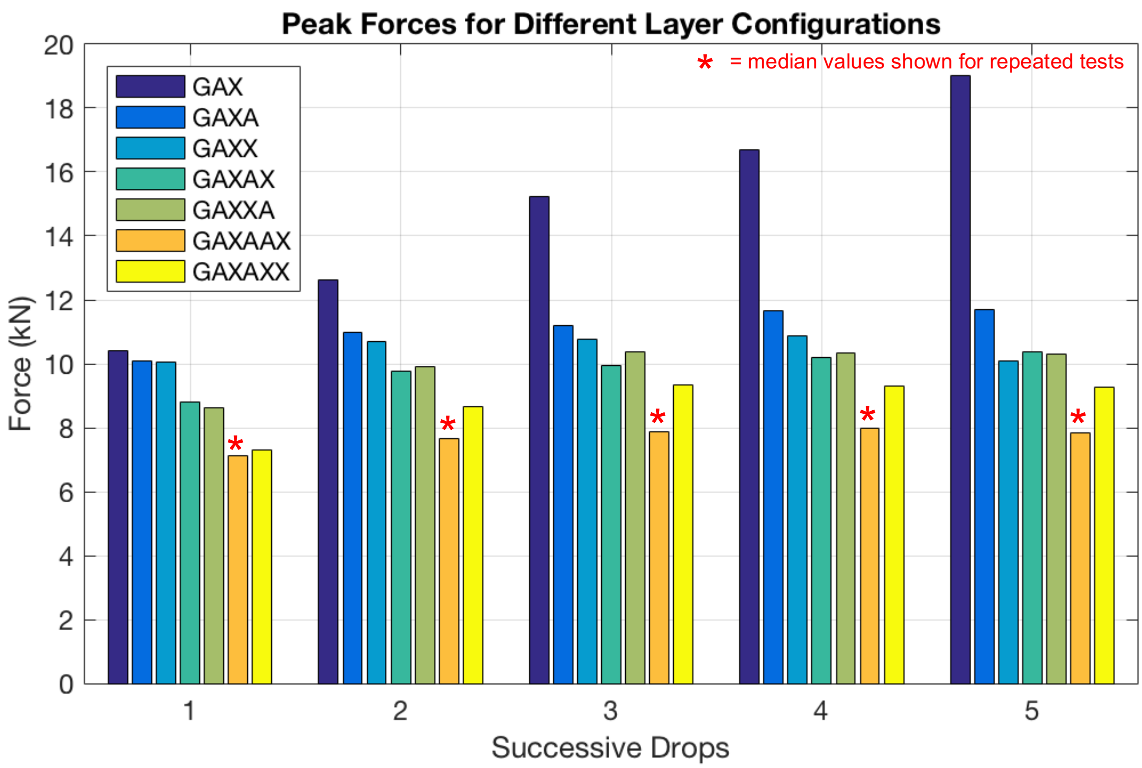


Figure 26: Comparison of peak forces for various configurations of Foam A and Isoblox X

The deterioration of the samples was also assessed by considering the change in peak force across the five successive drops. This was quantified as the force difference between drops 1-3, 3-5, and 1-5 (Table 8).

Table 8: Decline in performance of A/X configurations across successive drops

Configuration	**ΔF_{1-5} (N)**	**ΔF_{1-3} (N)**	**ΔF_{3-5} (N)**
GAX	8608	4833	3775
GAXA	1609	1113	496
GAXX	15	704	-689
GAXAX	1554	1124	430
GAXXA	1665	1757	-92
GAXAAX	726	619	107
GAXAXX	1953	2031	-78

4.3 Performance of different foam types

The GAX base layers were also used to compare the performance of the five foams A-E (Figure 27). Again, the material integrity after successive drops was assessed by considering changes in peak force between drops 1-3, 3-5 and 1-5 (Table 9).

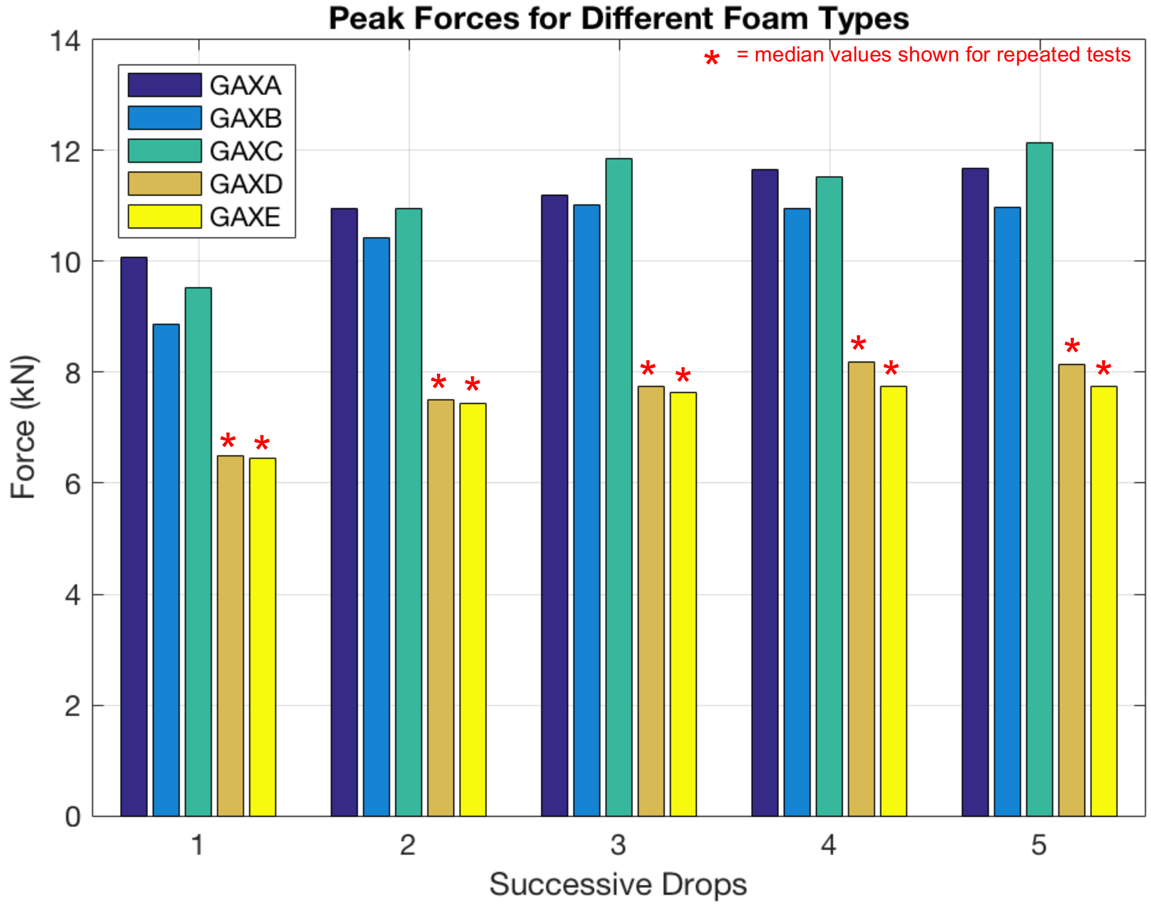


Figure 27: Comparison of peak forces for Foams A-E

Table 9: Decline in performance of foam samples across successive drops

Configuration	**ΔF_{1-5} (N)**	**ΔF_{1-3} (N)**	**ΔF_{3-5} (N)**
GAXA	1609	1113	496
GAXB	2116	2151	-35
GAXC	2618	2314	304
GAXD	1657	1249	408
GAXE	1306	1203	103

4.4 Performance of different Isoblox compositions

The new compositions of Isoblox (R, T, and Z) were compared with the original Isoblox X to assess whether they provide better protection (Figure 28). Note that testing of Isoblox R was stopped after four drops instead of five. The sound of impact during fourth drop indicated that damage to the sample was extensive compared to other drops. This prompted the data to be checked and it was found that the peak force reached 19.243kN. To avoid overshooting the capacity of the load cell and damaging the equipment, a fifth drop was not performed.

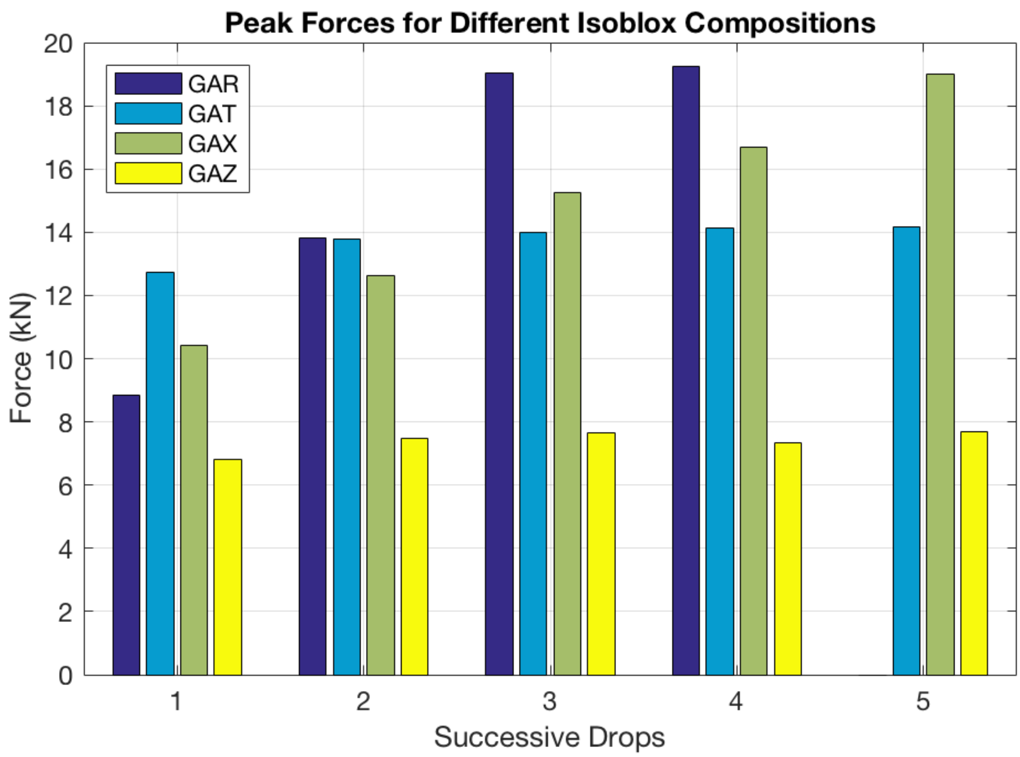


Figure 28: Comparison of peak forces for Isoblox compositions

The changes in peak force between drops 1-3 and 3-5 were calculated as an indication of material performance over successive drops (Table 10). Since only four drops were performed for sample GAR, the calculation was adjusted in this case to consider the changes between drops 1-3, 3-4, and 1-4 instead.

Table 10: Decline in performance of Isoblox samples across successive drops

Configuration	ΔF_{1-5} (N)	ΔF_{1-3} (N)	ΔF_{3-5} (N)
GAR	10390*	10186	204†
GAT	1441	1262	179
GAX	8608	4833	3775
GAZ	887	844	43

** ΔF_{1-4} (N) listed instead since fifth drop was not performed*

† ΔF_{3-4} (N) listed instead since fifth drop was not performed

4.5 Repeatability of optimal material samples

From the trends established above in Sections 4.2-4, the best performing materials were found to be GAXAAX, GAXD, GAXE, and GAZ. These samples produced peak force values in the range of 6.0kN to 8.2kN, and consistently performed better than other materials (Figure 26, Figure 27 and Figure 28).

Testing for samples GAXAAX, GAXD, and GAXE was therefore repeated to obtain data from three separate identical configurations, with five drops performed on each sample. This gave three peak forces values for each drop to be compared for consistency. Unfortunately, there was a limited resource of the Isoblox Z material, and so repeatability tests could not be undertaken for sample GAZ. The limited Isoblox Z material was instead used for later testing in Section 4.6.

Table 11: Peak forces (N) recorded for five successive drops on three samples of each configuration

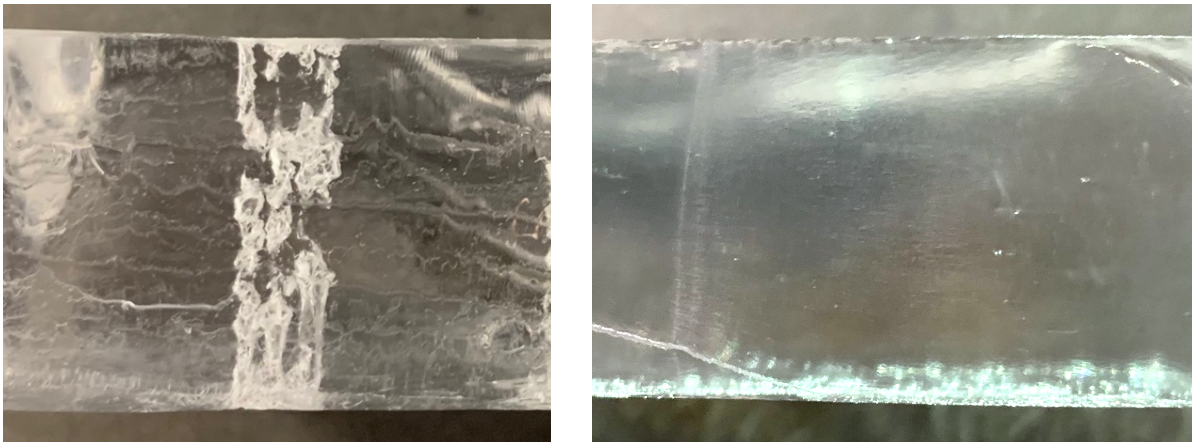
Configuration		Drop 1	Drop 2	Drop 3	Drop 4	Drop 5
GAXAAX	1	6302.0	7676.8	7917.5	8519.3	8553.1
	2	7127.1	7786.5	7745.8	7885.7	7802.9
	3	7326.1	7604.5	7875.1	7982.3	7852.5
	Range	**1024.1**	**182**	**171.7**	**633.6**	**750.2**
GAXD	1	6444.8	7513.1	7457.5	7663.0	8151.5
	2	6494.6	7248.2	7945.1	8247.4	8210.9
	3	6706.2	7708.1	7743.7	8182.4	8062.7
	Range	**261.4**	**459.9**	**487.6**	**584.4**	**148.2**
GAXE	1	6814.8	7582.9	7714.8	7867.9	7745.6
	2	6439.8	7440.5	7643.4	7746.8	7605.3
	3	5852.0	7028.8	7220.4	7487.1	7797.6
	Range	**962.8**	**554.1**	**494.4**	**380.8**	**192.3**

4.6 Performance of optimised material configurations

After validating the performance of samples GAXAAX, GAXD, and GAXE, it was found that the peak forces transmitted in sample GAXE were slightly lower than sample GAXD, but the thickness of Foam E (10mm) is greater than that of Foam D (6mm). The performance of Isoblox Z was clearly more desirable than other Isoblox compositions. Based on this, the client formulated an optimised configuration of materials involving the best-performing samples identified in Section 4.5. Combining Foam D, Isoblox Z, and the lay-up of GAXAAX, it was hypothesised that sample GAXDZ would have superior protective capabilities and reduce the peak force upon impact. The client also indicated an interest in testing GADZ as a secondary optimised material for comparison.

The two new optimised configurations were tested and the data was compared to previously identified optimal materials (Figure 30). An interesting observation to note was that all previous samples tested resulted in visible damage to the gelatine layer

(Figure 29a). However, the gelatine layers used to test these two new configurations (GAXDZ and GADZ) showed no visible damage after the five drops (Figure 29b).



(a) *(b)*

Figure 29: (a) Damage observed after drop testing in all previous gelatine layers (b) No visible damage in gelatine layers tested with optimised samples GAXDZ and GADZ

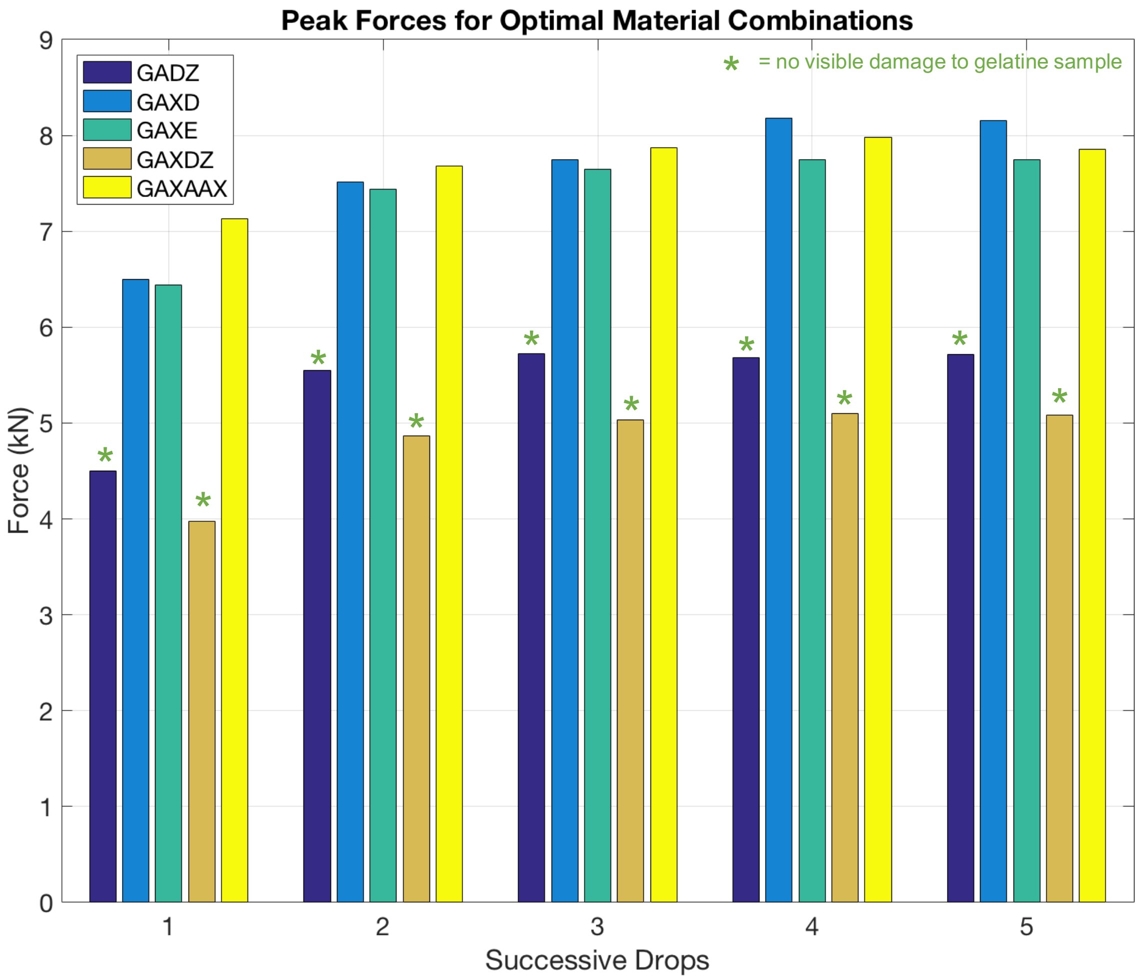


Figure 30: Comparison of new optimised material configurations (GADZ and GAXDZ) with previous samples

Table 12: Decline in performance of optimal samples between drops 1-3 and 3-5

Configuration	ΔF_{1-3} (N)	ΔF_{3-5} (N)	ΔF_{1-5} (N)
GADZ	1224	-7	1217
GAXD	1249	408	1657
GAXE	1203	103	1306
GAXDZ	1056	52	1108
GAXAAX	619	107	726

Chapter 5. Discussion

5.1 Relationship between peak force and contact time

By examining the force vs. time profiles (Figure 23 and Figure 24), the peak force experienced is highest upon the first bounce, and then reduces with successive bounces. This is because the impact of the masses on the material is an inelastic collision, where some kinetic energy is lost, causing the impactor to fall from a lower height after each bounce. This can be characterised by the COR, which is the ratio between the relative inbound and outbound velocities. While this is a commonly investigated parameter in assessing protective materials and may therefore prove to be an interesting future study, it is not the focus of this project, and so successive bounces within one drop test will not be discussed further. Instead, the peak force will be deduced from the first bounce, as this is most relevant in replicating the impact events in a cricket game.

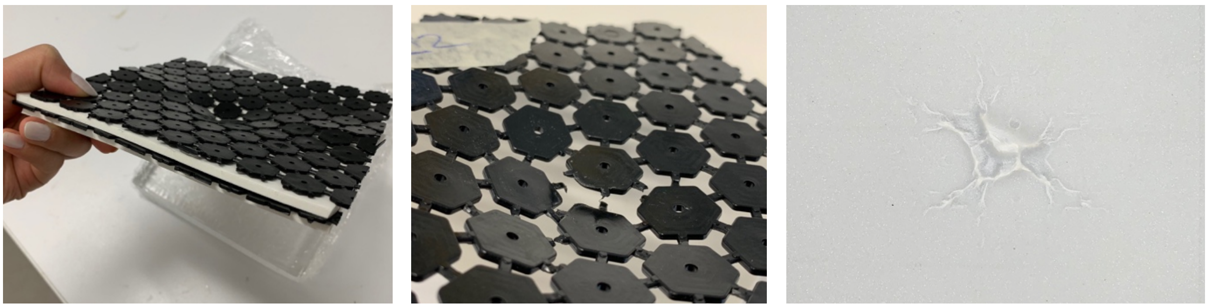
It is clear that the impact events occur very quickly, with the first bounce typically occurring in less than 0.01s, depending on the material. The relationship between force F and contact time t can be described by a parameter called impulse I, which is equal to the change in momentum of the system, Δmv (Equation 6).

$$I = Ft = \Delta mv \tag{6}$$

When the impacting unit is suspended before releasing the safety latch, the system has zero velocity and therefore zero momentum. Therefore, for the same initial conditions of mass and velocity, the impulse should theoretically be constant. Since the mass and velocity remain unchanged for all drop tests, it can be assumed that the impulse remains constant, with an inversely proportional relationship between peak force and contact time. Graphically, impulse is represented by the area under the graph of a force vs. time profile. Comparing drops with different peak forces, it can also be visually deduced that an increase in peak force is accompanied by a decrease in the time over which that force acts.

5.2 Change in material performance over successive drops

An unexpected finding was that the materials were permanently damaged after a single drop. This damage included either out-of-plane deformation of the plates and hinges (Figure 31a), fracture of the hinges (Figure 31b), or deformation of the foams (Figure 31c). This was not anticipated based on the results achieved in Isoblox testing from Ziegler (2016), where samples did not undergo visible damage after multiple impacts. However, it is important to note that testing from Ziegler (2016) involved drop energies in the range of 12.3-12.8J, whereas this protocol used over 66.2J. Furthermore, the materials tested by Ziegler (2016) were positioned on a flat steel base and therefore unable to deform. This protocol instead included a 20mm thick deformable layer of ballistics gelatine, allowing the material to flex and break, and more accurately replicating the damage that would realistically occur in a cricket game. Damage to the foams also included a circular dent in the impact region after each drop. However, the shape of the foam recovered over time (within a few hours), and flattened out again, retaining only the deformation due to pressure from the Isoblox sheet on top of it (Figure 31c).



(a) (b) (c)

Figure 31: Damage to material samples in the form of (a) permanent Isoblox deformation, (b) Isoblox hinge fracture, and (c) foam deformation

There is a clear difference in the performance of each sample as it endures successive drops. It is likely that as the damage to materials is compounded with each impact, less effective protection is provided and thus the peak force transmitted through the system increases. Since most of the damage occurs within the first three drops (as discussed later in this section), the values for $\Delta F_{1\text{-}3}$ (Table 8, Table 9 and Table 10) can be compared to assess the correlation between the extent of damage and the increase in force.

The least drastic increase in peak force resulted from sample GAXAAX, which reported an overall change of 619N between the first and third drop. There was obvious permanent damage to the sample in the form of out-of-plane deformation, but there were no visible hinge fractures in either of the two Isoblox sheets.

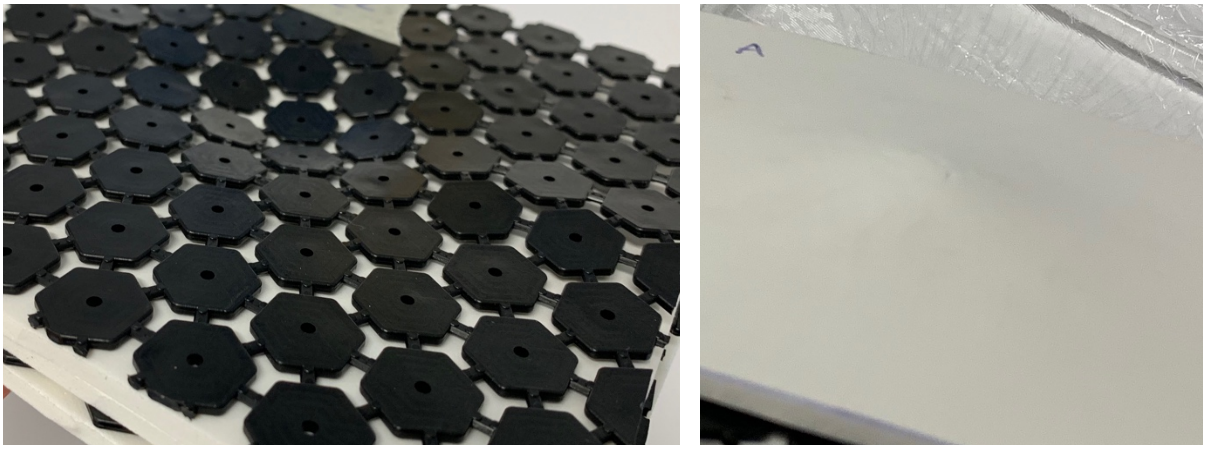


Figure 32: No visible hinge fractures in sample GAXAAX, resulting in a 619N increase between the first and third drop

While most samples showed an increase of less than 2314N, samples GAX and GAR returned a particularly drastic increase between the first and third drop, at 4833N and 10186N, respectively. Interestingly, the damaged observed to these samples was also notably more severe than other samples, with considerable deformation to the foam layer and a greater number of hinges being snapped (Figure 33 and Figure 34).

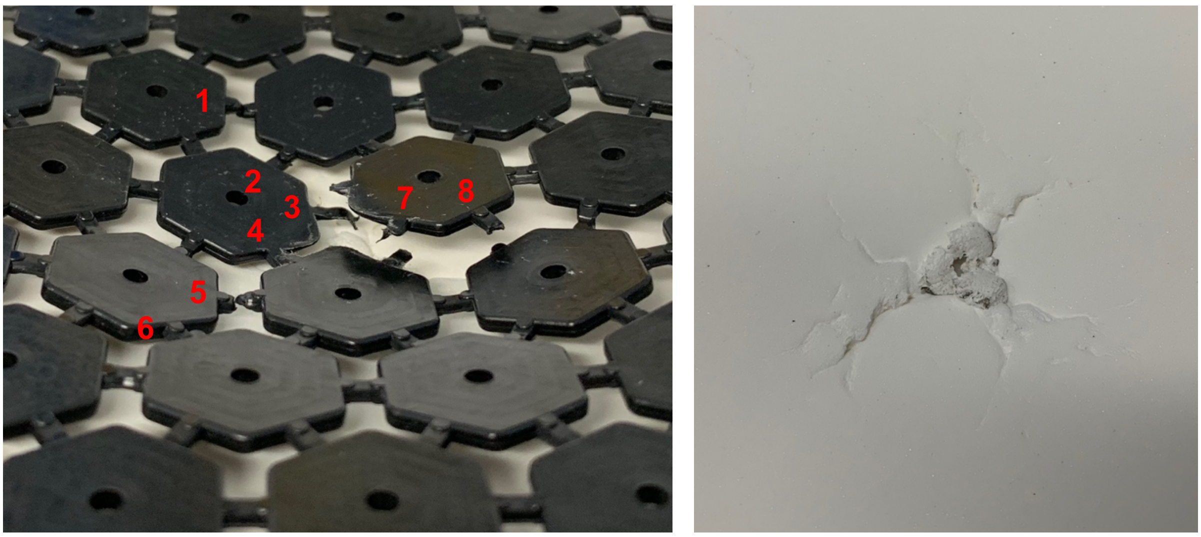


Figure 33: Sample GAX contained eight hinge fractures, reporting a 4833N increase between the first and third drop

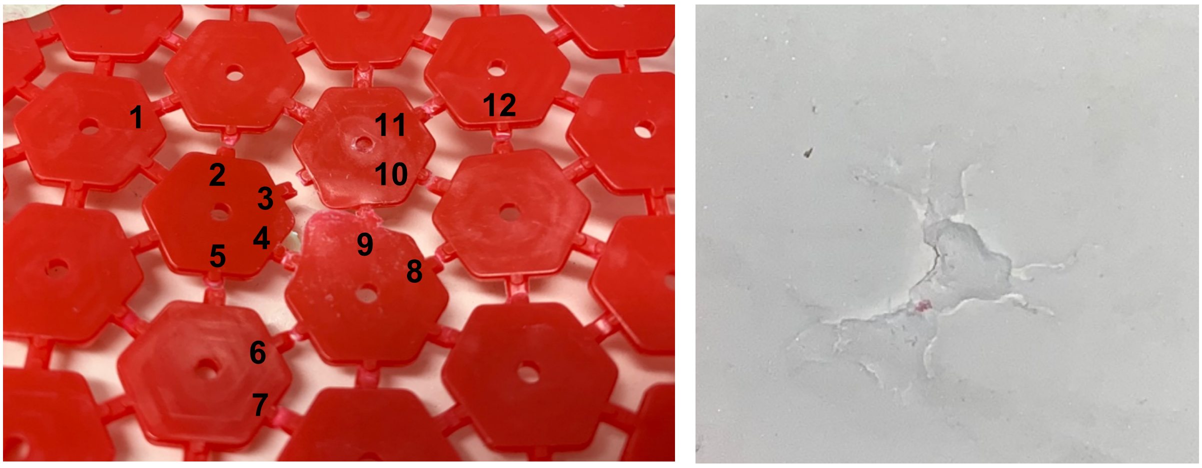


Figure 34: Sample GAR contained twelve hinge fractures, reporting a 10186N increase between the first and third drop

Based on the observations of damage and the reported change in peak forces, the results give a convincing indication that multiple drops compromise the protective capability of the material, with more extensive damage resulting in greater increases in peak force over successive impacts.

It is important to acknowledge that the gelatine also gets damaged with successive impacts, and this would contribute to the increase in forces observed. Visually, this damage is a vertical column extending through the entire gelatine cross-section, with internal tearing producing a cavitation effect in the sample (Figure 29a). The extent of damage can be correlated with the width of this column, which was observed to increase with each drop.

Another interesting trend that was consistent across all samples tested was that $\Delta F_{1\text{-}3}$ was greater than $\Delta F_{3\text{-}5}$ (Table 8 to Table 10), meaning that the increase in peak force was more significant between drops 1-3, compared to 3-5. This suggests that after the initial few drops, the material response plateaus and stabilises. It is difficult to gauge exactly how many drops would be required to reach this steady state, but from visual assessment of the graphs (Figure 26, Figure 27, Figure 28 and Figure 30), the peak forces for almost all samples tend to stabilise after three or four drops.

In some cases, the peak forces even decrease between drops 3-5. For the majority of samples that report a negative $\Delta F_{3\text{-}5}$, the decrease is in the range of 7N to 92N.

Sample GAXX is an outlier to this, with a peak force decrease of 689N. However, considering the magnitudes of peak forces being recorded, a change of 689N is still only 6.4% of the peak force value being measured (approximated based on data from drop 3 of GAXX), while a change of 92N is 0.89% of the peak force (from drop 3 on GAXXA). Also, the repeatability tests reported variations of up to 1024N across identical samples (Table 11), so these magnitudes are within the ranges of fluctuation. These differences can therefore be attributed to variances in the gelatine and material response, or might simply be a fluctuation due to the sampling rate used for data collection, which may not identify the exact peak. Other sources of error are discussed in Section 5.3 below. Regardless, the peak forces recorded on successive drops never reduces below the peak force recorded in the first drop. This implies that the material is most protective on its first impact, returning a lower transmitted force since it is undamaged.

5.3 Repeatability of testing and sources of error

The repeatability tests performed on materials GAXAAX, GAXD and GAXE highlighted variances across samples in the range of 148.2N-1024.1N (Table 11). It is difficult to assess the significance of these variances with only three samples of each configuration, but the results indicate that there is a need for further testing in order to establish the consistency of materials with a mean and standard deviation. No trends could be seen regarding the change in consistency of the materials with successive drops, and no correlation was shown between the magnitude of the forces measured and the magnitude of variations. Overall, it seems that the results are not extensive enough to draw a convincing inference about material consistency.

A possible source of variation across samples may be changes in the gelatine response. Since the gelatine is homogenous and an identical preparation method was used each time, an assumption was made that the samples would produce similar responses. However, testing the gelatine in isolation returned extremely short impact times, and the sampling frequency of the data acquisition system was inadequate in capturing the peak forces reliably. Therefore, the consistency of gelatine performance across different samples could not be confirmed.

It was observed that the extent of damage introduced to the gelatine with each drop differed depending on the protective capability of the material being tested. As established in Section 5.2, more extensive damage appears to contribute to a more substantial increase in peak force over successive drops. For materials with better protective abilities, the gelatine layer would not have greatly contributed to the force increase. However, gelatine tested with materials that provided less protection likely sustained more severe damage and therefore contributed more significantly to the increase in force. This means that the decline in gelatine performance was not constant for all materials, introducing a source of variability across testing of different configurations.

Another source of error is the position of the Isoblox sheets being tested, with respect to the centre of the impactor. This centre point is the first point of contact between the impactor and material, and is therefore the point at which the force is localised and transmitted through the system. Whether this point aligns with the hexagonal plate, the spaces in between, or the connecting hinges on the Isoblox sheet may influence the material response. From the damage observed across material samples (Figure 31), it is clear that the hinges are weaker as they are the first points of fracture. Therefore, impacting on the hinge rather than the plate may produce higher peak forces.

The foams exhibited elastic properties for the majority of tests and returned to their original shape after compression during impact, except in the cases where the foams sustained permanent damage. However, this was not an immediate response due to the foams' hysteresis behaviour, with energy being absorbed in the process. The extent of this energy absorption varied between the different foams types, and thus the recovery time was non-uniform across different foams. Before full recovery, the foam thickness is reduced, and therefore its density is effectively increased. Performing another drop on the foam before full recovery may result in a different response, because the initial conditions have been changed. Since drop tests were performed manually, the time between successive drops was difficult to measure, and was not kept constant. Consequently, there is a possibility that the differences in compression recovery across different foams contributed to errors in the measurement.

In a realistic setting on the cricket field, it is very unlikely that the material would sustain multiple impacts at the exact same region on the protective guard in a short time frame. It is therefore reasonable to assume that the foam can recover to its initial state before more trauma is endured, provided it was not damaged past its elastic limit. However, this hysteresis effect is still a worthwhile material characteristic to explore in future, to ensure that the guard can still perform adequately in the unlikely event that it receives repeated impacts in a short time frame.

It is also worth noting that the amount of energy applied in the system varied slightly for material samples of different thickness, as mentioned previously (Table 4). Thicker samples detracted from the set drop height, but the different was quite minor (ranging from 0.60m to 0.62m) and changed the input energy by only 2.3J at most. This is therefore considered insignificant for the scale of measurements being taken.

Despite these sources of variation, the repeatability tests still gave the same overall trends regarding the comparative performance of the optimal material configurations. Using three identical samples for each configuration, the results showed that the same trends could be replicated across samples. The tests were therefore meaningful in establishing the differences in protective ability for different materials and identifying a clear ranking from this selection.

5.4 Evaluation of best performing configurations

By combining the best-performing lay-up configuration, foam, and Isoblox composition, it was found that both the optimised configurations did indeed perform better than previous samples. The trends were consistent in showing that these two samples reduced the peak force transmitted in the system significantly, and allowed the materials to be ranked as follows (Table 13). The peak force shown is taken from the first drop on each sample, and median values are shown where repeated tests were undertaken. Since Isoblox Z has a curved surface, the value listed below represents the material thickness at its thickest point.

Table 13: Summary of best performing configurations

Ranking	Configuration	Thickness (mm)	Peak Force F_1 (N)
#1	GAXDZ	22.8†	3974
#2	GADZ	21.0†	4496
#3	GAXE	14.8	6440‡
#4	GAXD*	10.8	6495‡
#5	GAXAAX*	12.5	7127‡

** Ranking holds true for the first three drops only*

† Measured at maximum thickness of sample

‡ Median value taken from repeated testing

It is likely that replacing Foam D with Foam E to make a configuration of GAXEZ would produce even better results, based on the lower peak forces reported for GAXE compared to GAXD. However, the client selected Foam D for the optimised configuration as it is thinner, more compliant, and therefore more comfortable for the player to wear.

There is a general trend to indicate that increased thickness provides more protection, as expected. Sample GAXAAX is an exception to this, based on the first three drops where it produces higher peak forces than that of GAXD. However, due to the relative different levels of damage endured over successive drops in samples GAXD and GAXAAX, GAXAAX actually performs better than GAXD in the fourth and fifth drops. Regardless, sample GAXDZ (ranked #1) is clearly a superior configuration, resulting in a peak force of 3974N for the first drop. This is 522N lower than sample GADZ (ranked #2), and 2466N lower than sample GAXE (ranked #3).

Considering the fact that preliminary testing of samples GA and GX returned respective peak forces of 17639N and 13323N upon first drop, this is a sizeable reduction in peak force and a significant improvement in the amount of protection provided. Also note that the maximum transmitted force for a guard listed in BS 6183-3:2000 is 4000N to 6000N depending on the location and level of performance. Since these values were selected based on the force required to cause tibia fracture, the peak force of 3974N is a promising result.

Samples GAXDZ and GADZ (ranked #1 and #2 respectively) were also the only samples that protected the gelatine layer from any visible damage after five impacts (Figure 29b). This is a promising result that again clearly distinguishes these optimised sample as superior to the rest. This improvement is also corroborated by findings from visual inspection of the materials after testing. While GA and GX were damaged considerably after one drop (Figure 25), both samples GAXDZ and GADZ sustained minimal visible damage in the Isoblox Z and foam layers after five drops.

The Isoblox Z material did not appear to be damaged or deformed from testing of both GAXDZ and GADZ. Although the damage is difficult to assess because the gel is not completely transparent, no hinge fractures are visible in the sample (Figure 35). It is likely that embedding the Isoblox in gel provides structural support and impact absorption, which allows the hinges to remain intact during impact. However, in sample GAXDZ, the Isoblox X layer did show visible damage, with five hinges being fractured (Figure 36).

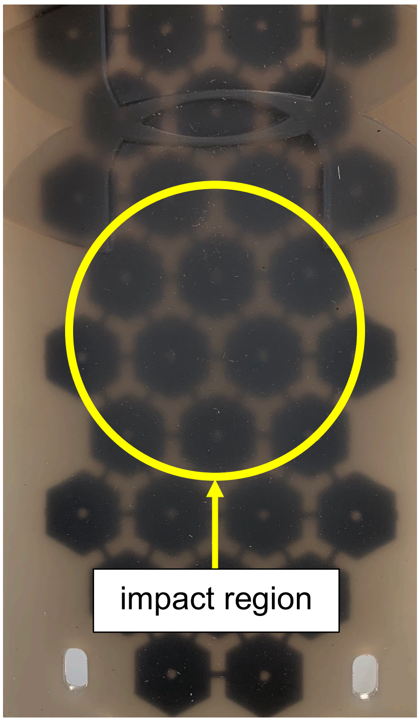


Figure 35: No visible damage to the Isoblox Z layer in samples GAXDZ and GADZ

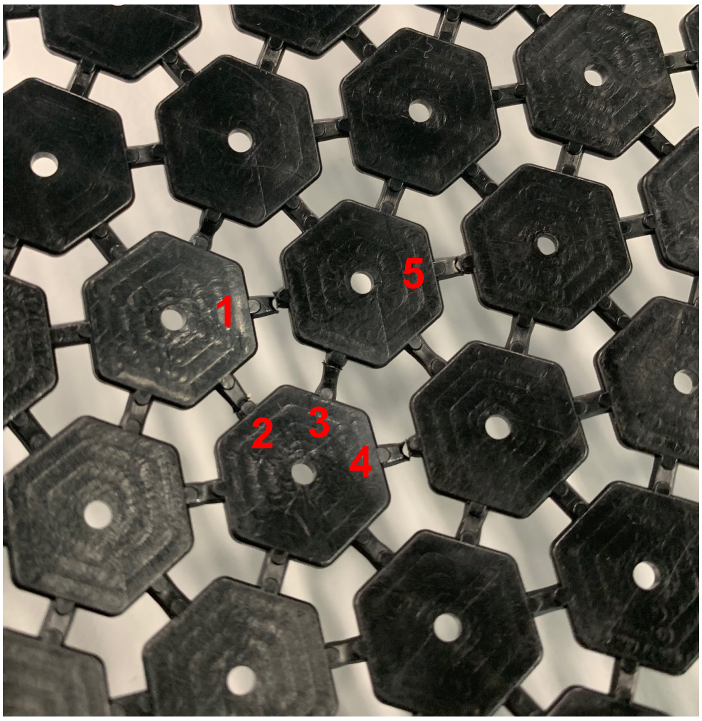


Figure 36: Five hinge fractures in Isoblox X layer after testing on sample GAXDZ

The fracture of hinges was observed frequently throughout testing, with hinges failing after five drops for the majority of samples. This is likely due to the hinges being stretched as the Isoblox sheet is deformed during impact. The observed damage highlights a worthwhile area of improvement, as it would not only strengthen the material upon the first impact, but also reduce the amount of degradation that is observed with successive drops thereafter. The current hinge design has a stress concentration due to the abrupt change in geometry and, although difficult to ascertain from the given images, the thickness of the hinges at the point of observed fracture is actually slightly less than the hexagonal plates. If the manufacturing process allows, it may be beneficial to maintain a constant thickness instead, and also add small fillets to the points of connection between the plates and the end of the hinges. These steps may minimise the stress concentrations present in the Isoblox X sheet, and ultimately improve the material performance.

It is worth reiterating that the repeatability tests previously discussed in Section 5.3 show variations in the range of 148.2N-1024.1N. The difference between the two best performing samples, GAXDZ and GADZ, is 522N, which falls within this range. Since Isoblox Z materials were limited, the optimal configurations could not be re-tested to assess repeatability. However, further tests on these configurations are recommended to ensure that this difference is indeed indicative of GAXDZ providing more protection than GADZ, and not a consequence of data variations or errors. Furthermore, Isoblox Z samples are designed with a slight curvature, such that the thickness is maximised at the centre and gradually decreases towards the edges. Knowing that a greater thickness typically provides more protection, the non-uniform thickness might affect results, depending on where the impactor lands on the sample. It might therefore be valuable to test the configuration at different locations on this layer, to verify that the sample still performs better than other configurations, even when impacted away from the centre.

5.5 Comparison of testing protocol and realistic impact events

The release of a ball-shaped impactor onto the material of interest in a drop tower set up imitates the impact that might be received during a cricket game using an equivalent energy basis. However, the drop tower was originally designed for a lower energy application, and so there were limitations in reaching the initial target energy of 130J set by the client.

Table 14: Comparison of initial target energy conditions and actual energy conditions executed in testing

	Energy (J)	Equivalent in-game ball velocity	
		(m/s)	(km/h)
Initial target value	130	39.9	143.8
Executed value	68	28.9	104.0

Comparing the velocities represented by the initial target energy and the value that was actually executed in testing (Table 14), the 68J applied to the samples does not replicate the typical speeds that are produced by fast bowlers at an elite level. However, the client has deemed this velocity to still be sufficient in representing the ball velocities delivered by the majority of recreational and competitive players.

It is also important to note that in a realistic impact event, it is likely that the player would move their limb away when anticipating impact, and upon being struck by the ball, the limb would recoil further. This motion has two main effects that are not considered in the drop tower setting, where the samples were fixed against the base plate: firstly, it increases the contact time between the ball and guard; and secondly, it contributes to energy dispersion. As established in Section 5.1, an increase in contact time reduces the peak transmitted force. Therefore, having a rigid set up where the material is fixed in place gives higher readings for peak force than that which would occur in a realistic setting where the limb moves with the impactor. While the ball may be bowled with a kinetic energy of 130J or higher, the recoil movement upon impact indicates a transfer of energy in the form of work done on the limb. This movement contributes to the energy dispersion achieved during the impact event. It is difficult to quantify these two factors, in terms of how much the contact time is increased and how much energy dispersion is provided due to this movement, but it is reasonable to deduce that the testing overcompensates with the energy applied, and likely exaggerates the damage that the protective material would encounter. Furthermore, a realistic impact would involve a slipping motion of the guard against the limb, as well as slight displacements of the materials within the casing, since they are not bound together. These additional mechanisms through which energy is dispersed in an impact event may be the reason why the official testing standard calls for testing at only 10J, 20J or 40J of energy (depending on the performance level being assessed).

There are also many other factors involved in a realistic impact event that could not be replicated experimentally by drop testing. The materials will be formed with a curvature so that the guard can be fitted to the limb. This flexure might show differences in impact dispersion and damage patterns. As previously discussed in Section 5.3, the testing performed did not take into account the foam recovery behaviour, and depending on the rate of recovery, it is likely that successive drops were conducted before the foam was able to fully recover. During a cricket game, it is unlikely that impacts will occur at this frequency, and at the exact same location on the guard. If more time was given between successive drops, the foams may show better performance in reducing the peak force transmitted.

The realistic in-game velocity of 28.9m/s that is correlated with the 68J of energy used could not be replicated in the drop tower. Based on the law of conservation of energy, the potential energy when the impactor is suspended is transferred to kinetic energy as it falls and reaches the sample. Therefore, the actual impact velocity in the drop tower is dependent on the drop height, according to Equation 7.

$$v = \sqrt{2gh} \tag{7}$$

Representing this impact velocity of 28.9m/s would require a height of 42.57m, which is obviously not feasible. Instead, using a drop height of 0.62m gives an impact velocity of 3.49m/s. It is known that the foams used, PE and EVA, exhibit viscoelastic properties where the stiffness changes depending on the rate of loading (Penta *et al.*, 2018; Yang, 2018). For example, the compressive stress-strain curve for EVA indicates a higher stiffness for higher strain rates (Figure 37).

Figure has been removed due to copyright restrictions.

Figure 37: Increased stiffness for increased strain rates observed in compression of ethylene-vinyl acetate (EVA) during loading and unloading. Reproduced from Penta et al. (2018).

This is dictated by factors such as the material cellular composition and density. Consequently, the velocities received in an impact event during a cricket game may induce different responses from the protective material, compared to the loading that was applied in the drop tower.

The factors of difference between the testing protocol and the types of impact that would be received in a cricket game may certainly influence the impact conditions and material response. These factors should be considered in future prototype testing to validate the material performance under more realistic conditions. However, it is important to reiterate that the testing was conducted on a comparative basis, with energy deemed the most important factor to replicate. The general trends and comparisons between different material samples remain valuable as an indication of which configurations are worth testing further in future.

5.6 Limitations of methods used

In developing a testing protocol to assess the comparative peak forces transmitted by different materials, many limitations were identified. The first major limitation of using the drop tower was that the height was restricted to 0.64m, from the bottom of the impactor to the base plate surface. This required testing with a mass 20.7kg to reach 130J, which was very strenuous to lift manually and therefore posed an occupational health and safety risk. Furthermore, preliminary testing indicated that the forces transmitted at this level of energy would have been damaging to the load cell. Considering the fact that some of the results obtained at only 68J of energy reached over 19kN, it is clear that testing at 130J would have surpassed the 20kN capacity of the load cell. Fortunately, this did not pose a significant problem, because comparative trends could still be obtained at lower energy levels. Replicating the full energy of the cricket ball is also excessive, following the argument presented in Section 5.5 about other energy dispersion methods that are not replicated in the drop tower. Additionally, BS 6183-3:2000 does not require testing at more than 40J, and the client was satisfied with the conditions that are represented by 68J of energy.

As mentioned above, some peak forces measured in testing approached the maximum capacity of the load cell. This prevented the 20mm gelatine samples to be tested for consistency, as the unprotected gelatine G would result in very high peak forces based on the results obtained from single-layer samples GA and GX. The consistency of gelatine across different samples could not be confirmed. Aside from this, the limitation in load cell capacity did not majorly affect the results, aside from one peak force value for the fifth drop on sample GAR that could not be obtained (Section 4.4). However, as it was difficult to predict the peak force range that would result from each material sample upon first drop, and so testing required a high degree of caution. Caution was exercised particularly for thinner material samples, and as shown in the case of sample GAR, the sound of the drop was used as a indicative guide for whether the results needed to be checked before successive drops were continued. Based on the observation of increased peak forces over successive drops, particularly for samples that encountered severe damage, this maximum capacity may be problematic if material performance over a greater number of drops is investigated in future.

The 5kHz sampling rate used in testing introduced doubt about whether the true peak force was being captured reliably. This sampling rate was set in the NI SignalExpress software based on advice from the engineering services department, to ensure that recording was compatible with the load cell specifications and avoided excess noise in the data. The comparisons drawn from the results recorded at this frequency are considered valid, based on the consistency of trends observed across successive drops, and across repeated samples. However, considering the difference between the data captured at 2kHz and 5kHz (Appendix E), sampling at 10kHz would be advantageous in confirming the trends that were established. This capture rate is deemed adequate in capturing peak forces during impact, according to the requirements of BS 6183-3:2000.

Another deviation from the testing methods outlined in BS 6183-3:2000 is the position of the load cell. Rather than being placed beneath the base plate (or anvil) that supports the samples (Figure 4), the load cell was attached above the impactor. This positional change should not change the forces measured during impact, as the force is transmitted linearly through the entire system, and is therefore uniform from the top of the impacting unit, to the bottom of the base plate. The only difference that might be expected, if moving the load cell from above the impactor to beneath the base plate, is a slight time delay in the force recording. However, the magnitudes theoretically remain unchanged.

Other limitations faced were time delays associated with setting up the drop tower, so that it would be suitable for this application. Designing and manufacturing new parts involved consultations and revisions with the engineering services team. After initial testing, it was also found that the adaptor piece, which is critical in attaching the impactor to the system, needed replacement due to wear and loosening. Unexpected delays also arose with problems in the initial data collection, where results did not make theoretical sense due to the filtering settings that were incorporated in the software. These setbacks reduced the timeframe reserved for drop testing, meaning that the order of testing on different configurations had to be very selective to ensure the most meaningful outcome of results, despite a limited number of tests.

Finally, the damage observed in the gelatine samples after testing on each sample meant that the gelatine could not be reused for multiple tests. The re-melting process was beneficial, as it meant that the gelatine could be reused rather than purchasing new blocks, but it also limited the amount of testing that could be done. For comparison, performing five successive drops on one material sample took about ten minutes, whereas melting and setting a single gelatine sample took two hours. The gelatine samples were therefore continuously being re-melted and used throughout the testing process, in order to test all material samples with a new gelatine layer each time.

Chapter 6. Conclusions

6.1 Summary of findings

By establishing an effective impact testing protocol, this project has presented a thorough and detailed evaluation of suitable methods to compare protective guard performance. Initial testing performed previously by Ziegler (2016) and standard procedures outlined in BS 6183-3:2000 were assessed in this process. The key differences in the testing protocol used in this project are the higher levels of energy applied to samples (at 68J compared to less than 40J in other methods), and the use of ballistics gelatine beneath the materials to imitate human soft tissue. These factors provided a more realistic set up and highlighted new insights, particularly regarding the type of damage encountered by the materials.

Results indicated that the best performing foam was Foam E (PE of 120kg/m^3 density and 10mm thickness) followed by Foam D (PE of 140kg/m^3 density and 6mm thickness). Foam D was preferred by the client due to its flexibility and reduced thickness. The most protective Isoblox composition was found to be Isoblox Z (Isoblox layer embedded in gel), and the most effective lay-up was GAXAAX. Based on consultation with the client throughout the entire project, two optimised configurations were selected, which combined the best performing materials from each preliminary study. Results confirmed that these configurations exhibit more significant peak force reduction abilities compared to other samples. Based on the peak transmitted force recorded upon the first impact, GAXDZ reported the best performance, at 3974N, followed by GADZ, at 4496N.

Overall, damage was observed in all samples, with fractures to the hinges, or permanent deformation to the Isoblox and foam layers. Through visual inspection of material samples, a point of weakness was identified in the connecting hinges of the Isoblox layer. It is recommended that this is considered as a focus for future material design improvements. The severity of damage typically correlated with an increase in the peak forces measured in successive drops on the same sample, with the most drastic increases found within the first three drops, before the peak forces stabilised after the third or fourth drop. It is important to note that repeatability studies reported a considerable fluctuation in peak force values, in the range of 148.2N-1024.1N. Further testing is therefore recommended to verify the trends and confirm that the best performing configurations can be clearly distinguished from others.

6.2 Recommendations for future works

There are many areas of improvement that are recommended for future testing of sports protective materials, as well as opportunities for further development in this project that should be undertaken before product commercialisation. These involve improvements to the current drop testing protocol, as well as directions for future studies in order to test the prototype guards in a more realistic setting. The recommendations are listed below in order of priority.

6.2.1 Improvements to drop test protocol

- *Increased load cell capacity of 50kN:* The load cell was a significant limitation that prevented complete testing of single-layer samples, or samples that endured severe damage. The decision to select a new load cell with the above metric is based on the specification outlined in the testing standard, BS 6183-3:2000. Purchasing this load cell will improve current testing methods, and provide opportunities to test according to the standard protocol in future as well before commercialising the final product.
- *Increased sampling rate of at least 10kHz:* The peak forces associated with isolated gelatine layers could not be assessed for consistency as the 5kHz sampling rate was speculated to be insufficient. Again, the new metric of 10kHz was selected following the BS 6183-3:2000.
- *Further repeatability studies for optimised material configurations:* Current repeatability results did not show clear trends about the consistency of peak forces over successive drops across different samples. Assessing a greater number of samples for each configuration would allow for better analysis to identify whether a statistically significant difference is observed between materials. A greater number of drops per sample could also be performed so

that the long-term performance of materials can be assessed beyond five impacts.

- *Comparative testing against competing brands:* Testing by Ziegler (2016) showed that the Isoblox samples provided more protection than guards made by competitors such as McDavid, Nike, Under Armour, G-Form and Evo Shield. It is recommended that these competing products are obtained and tested using the protocol presented in this thesis to verify the trends, considering the influence that the differences in protocols might have.
- *Obtain displacement data using a laser sensor:* This would be valuable data in confirming the exact contact time between the impactor and material, which is often difficult to discern exactly from the force vs. time graphs. The laser displacement sensor may be positioned on the underside of the impacting unit next to the impactor, and can be synchronised with the load cell data using the existing NI cDAQ-9178. This data would allow for calculation of velocity before and after impact (therefore indicating the COR for different materials), and is advantageous over other displacement sensors as it provides high resolution, and does not require alterations to the sample or extensive post processing.
- *Inspect damage to material using high-speed camera:* Having a visual record of the impact event when the impactor contacts the sample may allow the mechanism of damage to the sample to be qualitatively gauged. This may provide insight about the stress concentrations or points of weakness in the sample, which may be valuable in future improvements to the material design.

6.2.1 Guard prototype testing on gelatine model of limb

There are many notable differences between a realistic in-game impact event and the replicated scenario in the drop tower. Another phase of testing should be pursued to imitate the realistic event more closely, and may follow the recommendations listed below.

- *Impact provided by bowling machine used in cricket training:* Access to the South Australian Cricket Association may be obtained through the client, in order to impact a prototype guard with a real 163g cricket ball fired from a bowling machine. The cricket ball differs to the nylon impactor used in the drop tower in material and symmetry, due to its rolled core construction and leather casing. It exhibits hysteresis, showing a degree deformation during impact, and may therefore behave differently when interacting with the protective material. Firing the ball towards the guard will also introduce differences compared to a vertical fall, such as the effect of impact angle.

- *Testing with completed guard prototypes, including casing and attachment straps:* Testing the materials in the form of a guard prototype will allow for effects of slippage between material layers, displacement of the guard against the limb upon impact, and any differences that the guard curvature may introduce. Development of the prototype must consider design requirements such as comfort, flexibility and fit. By this stage of development, it is hoped that the Isoblox design will have been improved to minimise stress concentrations in an attempt to prevent premature damage to the guard, so that multiple impacts can be endured by the same guard. Testing can also compare the guard's performance under impact at the central region and towards the edges.
- *Realistic gelatine model of limb:* The thigh, forearm or chest could be modelled using gelatine by creating an appropriate mould. Again, this would introduce the effect of curvature, as well as a non-uniform soft tissue thickness underlying the protective material. Note that the gelatine remelting instructions differ for plastic moulds compared to metal moulds, and therefore resources from Clear Ballistics should be consulted for further details.
- *Embed accelerometers in gelatine:* The sensor cannot be attached to the cricket ball, since it could potentially affect the ball's flight path or be damaged in the process. However, the advantage of the remelting method for gelatine preparation is that there is an opportunity to embed sensors within the gelatine as it cools in the mould. Inserting an array of sensors at the impact point and surrounding region could allow the transmitted force received upon impact to be measured, and the spread of this force to be quantified. This may also provide an opportunity for a more direct comparison with the initial testing by Ziegler (2016), which reported results in the form of peak g values.
- *Secure gelatine limb on a moveable rig:* To imitate the body's movement in response to impact, the limb may be placed on a rig that allows for translation and rotation in the direction of impact. This may be complex to model depending on the chosen limb, but the opportunity for limb motion would come closer to

the realistic impact event compared to the rigidly fixed sample at the base of the drop tower.

The trends established from the results of this project contribute significant insight into the future directions that should be taken for further development of Isoblox guards. The project was not only valuable in outlining the current optimal materials, but also in providing reasoning and justification for the requirements of a rigorous and reliable method to be implemented for future testing. Overall, this thesis has satisfied the client requirements of establishing an optimal configuration to be incorporated into a product prototype for commercialisation, and has successfully contributed to the end goal of providing body protection to players of all ages and skill levels. The research presented has focused on impact events that occur in cricket, but the knowledge may be transferred to assess the impact protection provided by guards used in other sports, as well as protective materials used in wider applications.

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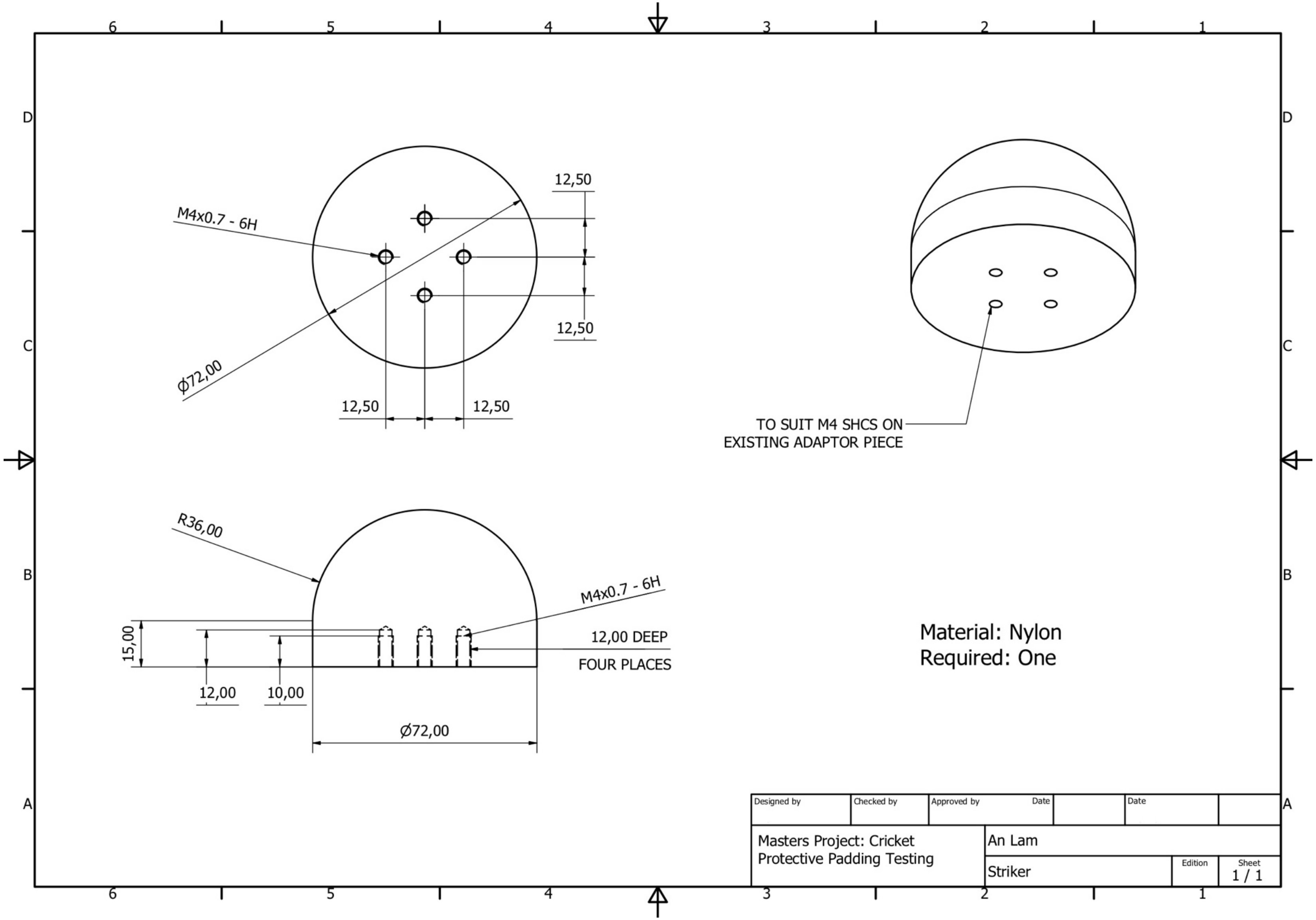
Appendices

Appendix A: Load cell specification data sheet (Kelba, 2018)

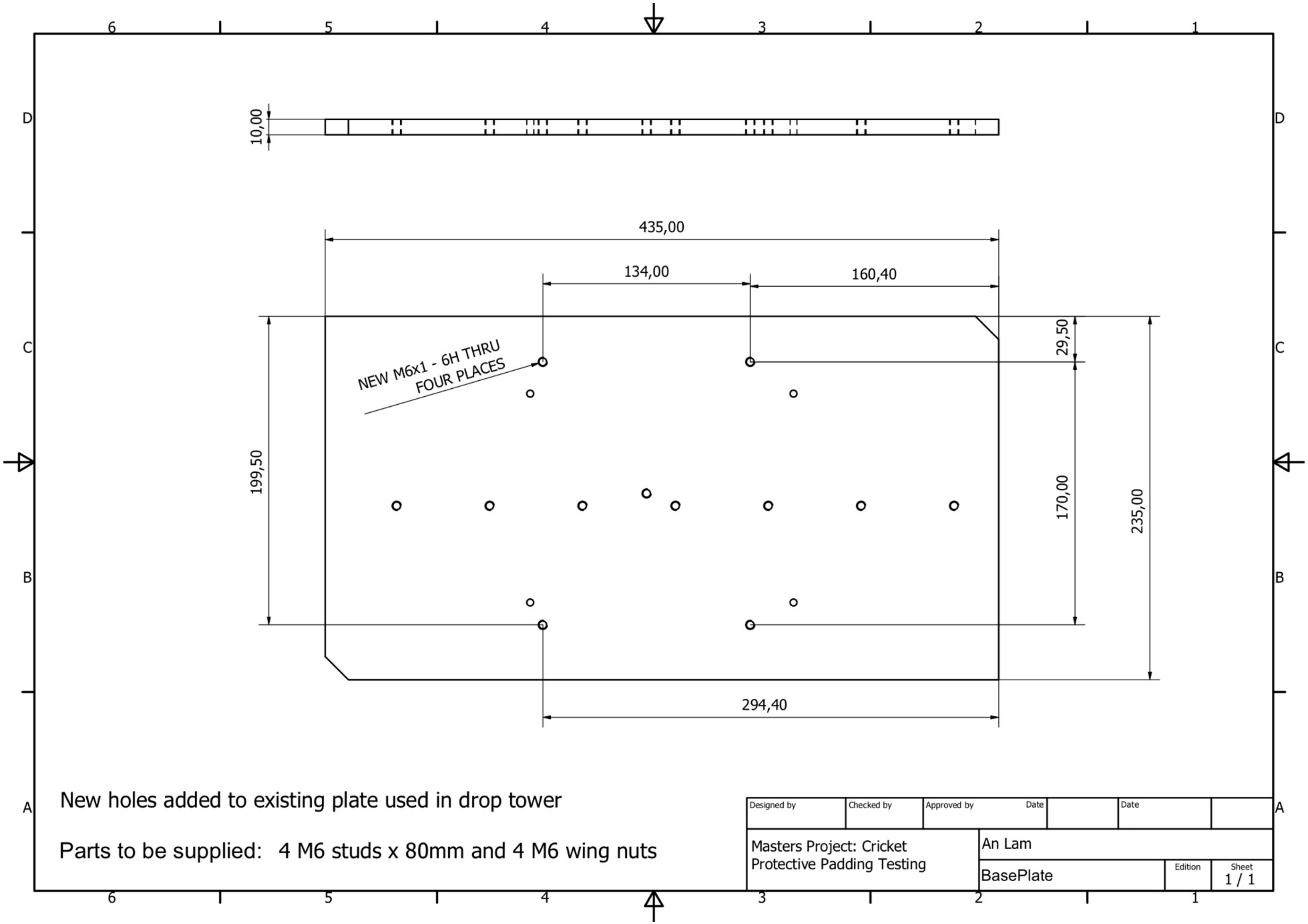
Appendix A has been removed due to copyright restrictions.

Appendix B: Engineering drawings for drop tower components

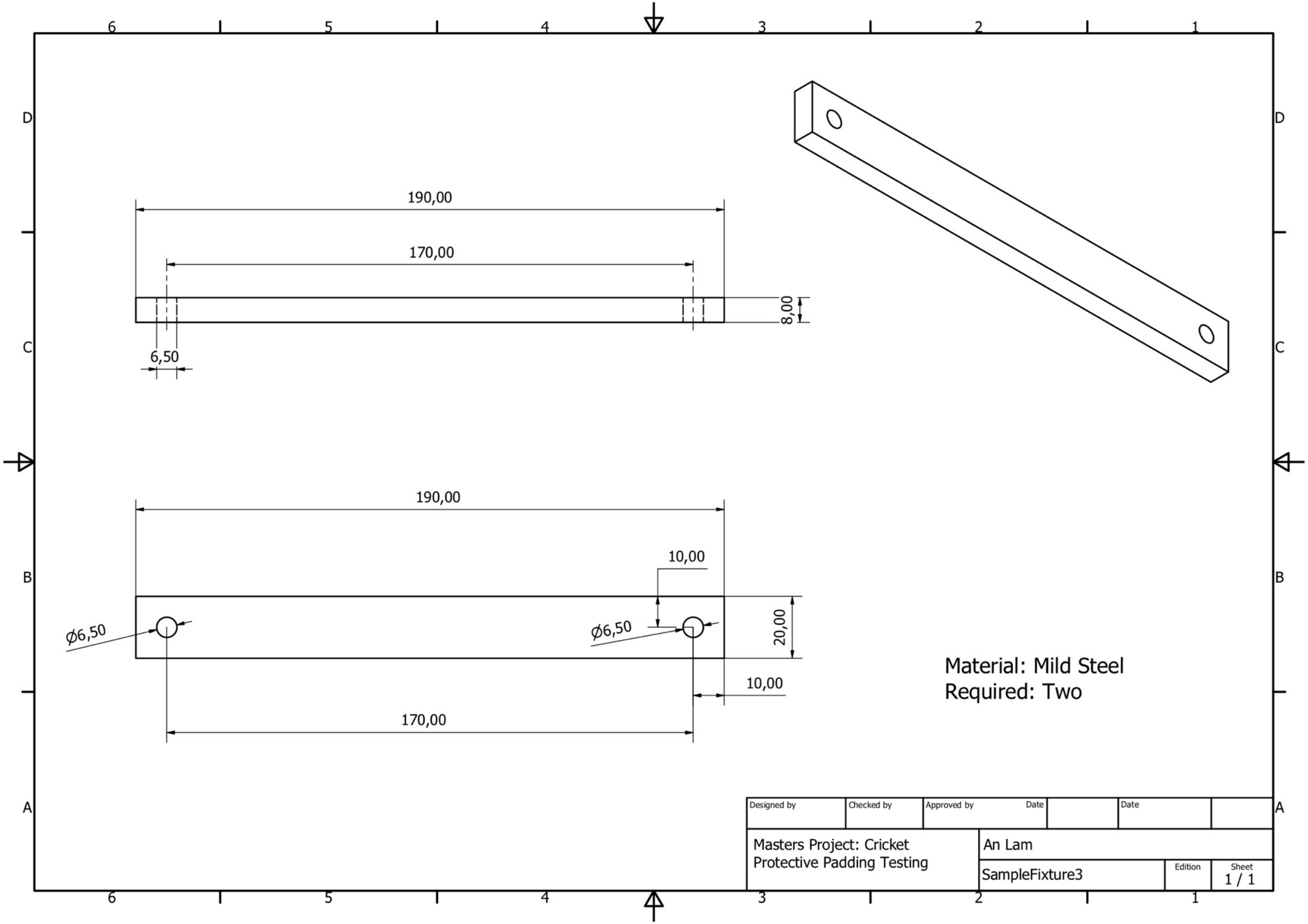
B.1 Impactor



B.2 Base plate



B.3 Sample Fixtures



Appendix C: Clear Ballistics MSDS

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Appendix D: Clear Ballistics Remelting Instructions

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Appendix E: Inconsistent results for 10mm gelatine samples

Peak forces recorded when applying 23J of impact energy to isolated gelatine layer.

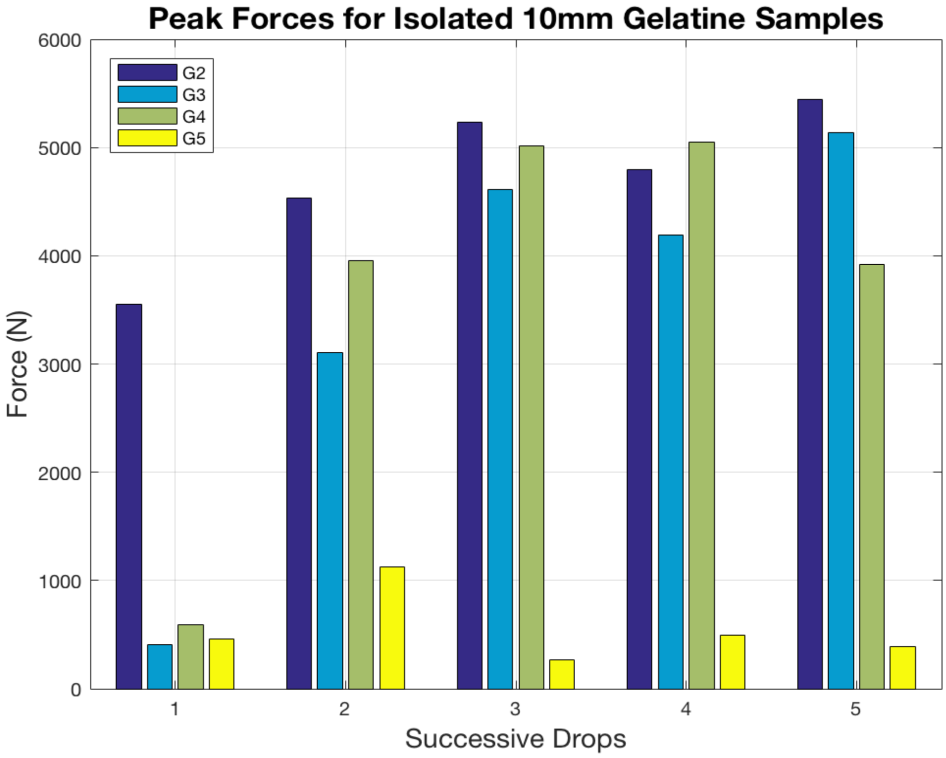

Figure 39: Peak forces captured at 2kHz sampling rate

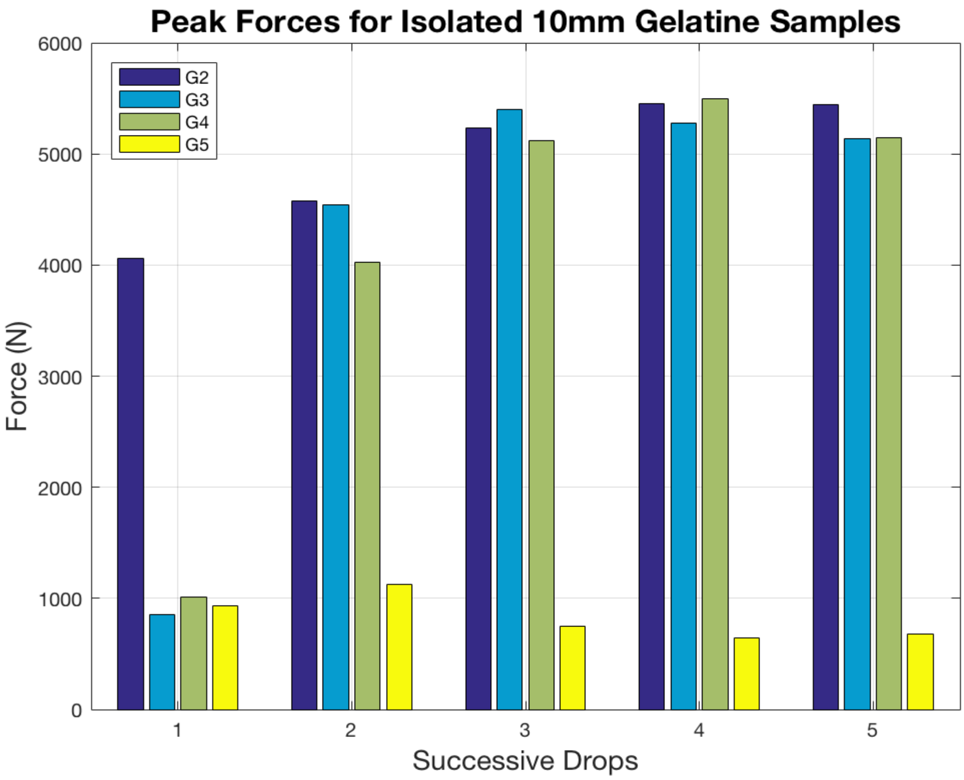

Figure 38: Peak forces captured at 5kHz sampling rate

Appendix F: Index of sample configurations tested

G	gelatine (20mm thickness, unless otherwise indicated)
X	original Isoblox (black)
R	new Isoblox (red)
T	new Isoblox (transparent)
Z	original Isoblox embedded in gel
A-E	foam type

Table 15: Number of drops and samples tested for each configuration

Configuration (bottom to top)	Drops per sample	No. samples tested
G (10mm) *	5	5
G *	5	1
GA	1	1
GX	1	1
GAX	5	1
GAXX	5	1
GAXA	5	1
GAXB	5	1
GAXC	5	1
GAXD	5	3
GAXE	5	3
GAR	5	1
GAT	5	1
GAZ	5	1
GAXAX	5	1
GAXXA	5	1
GAXAXX	5	1
GAXAAX	5	3
GAXDZ	5	1
GADZ	5	1

** tested at lower energy level (23.3J using 3.77kg of mass at a height of 0.63m)*

Appendix G: Masses of impacting unit and related parts

Table 16: Masses of impacting unit

Part	Mass (kg)
Top securing nut	0.034
Rod	0.300
Impacting unit top bracket	1.206
Impacting unit base	1.678
Load cell	0.291
Screws	0.014
Striker and adaptor piece	0.247
TOTAL	**3.770**

Table 17: Masses of discs

Part	Mass (kg)
Small disc 1	2.492
Small disc 2	2.495
Large disc 1	4.989
Large disc 2	4.991
Large disc 3	4.991
Large disc 4	4.992
TOTAL	**24.95**

Table 18: Masses of extra small parts

Part	Mass (kg)
Secondary nut	0.032368
Short bolt	0.140386
Small cylinder	0.010573
Medium cylinder	0.021749
Large cylinder	0.032518
TOTAL	**0.237594**

Appendix H: MATLAB scripts for data analysis

H.1 DataProcessor_ReadIn.m

```
% DataProcessor_ReadIn - ENGR9700 Masters Thesis
% Optimisation and impact assessment of
% novel protective guards used in cricket
%
% - Imports F vs. t drop test data from SignalExpress .csv files
% - Extracts material information from file name and sorts into fields of
data structure
% - Saves time, force and peak force data to structure
% - Orders structure by number of layers and saves to file
% - Data structure to be used by subsequent script:
%           DataProcessor_Plot.m
%
% - File naming system:
% - [material][samplenumber].[repeat]_[date]
% - Refer to Appendix F for material labelling key
%
% An Lam, 2019

close all; clear all;

% Load all data files (*.csv) in this directory
fn=dir('*.csv');

% Create cell array to contain file names
fnam=cell(length(fn),1);

if isempty(fn)                    % If  directory does not contain .csv files
    fnam=[];
else
    for i=1:length(fn)
        fnam{i}=getfield(fn,{i,1},'name');  % Extract file name
        % Manipulate file names to deduce relevant information for each
sample
        raw(i).material=fnam{i}(1:end-13);          % Material name
        raw(i).sample=fnam{i}(1:end-12);            % Sample name
(indicates repeats)
        raw(i).drop=str2num(fnam{i}(end-10));       % Drop number (1-5)
        raw(i).repeat=str2num(fnam{i}(end-12));     % Repeat number (1-3)
        raw(i).layers=length(raw(i).material)-1;    % Number of layers

        % Import force and time data
        import=csvread(fnam{i});

        % Save force data to structure
        F{i}=import(:,2);
        raw(i).force=F{i};

        % Create time vector to match frequency and length of force data
        l=length(F{i});
        time=0:0.0002:(l-1)*0.0002;
        t{i}=time.';                   % Transpose from row to column vector
        raw(i).time=t{i};              % Save time data to structure
```

```
        % Save peak force data to structure
        raw(i).peak=max(F{i});
    end
end

% Convert raw data to table and sort according to number of layers
T=struct2table(raw);
orderedT=sortrows(T,'layers');
data=table2struct(orderedT);

% Save ordered structure of data to file
save('data.mat','data');

% Save all fields (excluding full force and time data) to file for
reference
peaks=orderedT(:,[1,2,3,4,5,8]);
writetable(peaks,'peaksdata.xlsx');
```

H.2 DataProcessor_Plot.m

```
% DataProcessor_Plot - ENGR9700 Masters Thesis
% Optimisation and impact assessment of
% novel protective guards used in cricket
%
% - Loads data structure containing material information and peak force
results
% - Data structure retrieved following preceding script:
%           DataProcessor_ReadIn.m
% - Identifies repeated tests for optimal materials
% - Calculates median and range values for repeated tests
% - Categorises all data into four separate arrays for plotting:
%       1. Isolated gelatine
%       2. Isoblox compositions
%       3. Foam types
%       4. Lay-up configurations
% - Sorts data into separate drops for each sample
% - Saves tabulated peak force data to file for easy reference
% - Plots all peak force data to four separate bar graphs
%
% An Lam, 2019

% Remove variables from workspace and retrieve test data
close all; clear all;
load('data.mat');

% Find repeated tests and sort peak force data into arrays
for i=1:length(data)
    if strcmp(data(i).material,'GAXD')
        GAXD(data(i).repeat,data(i).drop)=data(i).peak;
    end

    if strcmp(data(i).material,'GAXE')
        GAXE(data(i).repeat,data(i).drop)=data(i).peak;
    end

    if strcmp(data(i).material,'GAXAAX')
        GAXAAX(data(i).repeat,data(i).drop)=data(i).peak;
    end
end
```

```
% Output median and range values for repeated samples
GAXDrange=max(GAXD)-min(GAXD)
GAXDmedian=median(GAXD)

GAXErange=max(GAXE)-min(GAXE)
GAXEmedian=median(GAXE)

GAXAAXrange=max(GAXAAX)-min(GAXAAX)
GAXAAXmedian=median(GAXAAX)

% Create empty variables to contain peak force values and legends
% Initialise counter variables to identify successive drops for same sample
gel=[];         % Contains isolated gel data
gl={};
g=1;

isoblox=[];     % Contains Isoblox data
xl={};
x=1;

foams=[];       % Contains foam data
fl={};
f=1;

config=[];      % Contains AX material configurations data
cl={};
c=1;

% Iterate through all drops contained in data structure
for i=1:length(data)
    % Row of each matrix correpsonds to drop number (1-5)
    n=data(i).drop;

    % Save to gelatine matrix if material name is 'G'
    if strcmp(data(i).material,'G')
        if data(i).drop==1                  % Increment counter for each
new sample
            g=g+1;
        end
        gel(n,g-1)=data(i).peak/1000;       % Convert from N to kN
        gl{g-1}=data(i).sample;             % Legend contains sample name

    % Save to Isoblox matrix if configuration consists of 2 layers only
    else if data(i).layers==2
            if data(i).drop==1 && strcmp(data(i).material,data(i-
1).material)==0
                x=x+1;
            end
            isoblox(n,x-1)=data(i).peak/1000;
            xl{x-1}=data(i).material;       % Legend contains material name

            if strcmp(data(i).material,'GAX')       % If GAX, also save to
configurations matrix
                if data(i).drop==1 && strcmp(data(i).material,data(i-
1).material)==0
                    c=c+1;
                end
                config(n,c-1)=data(i).peak/1000;
                cl{c-1}=data(i).material;
            end
```

```
        % Save to foams matrix if configuration consists of 3 layers and if
        % material name starts with GAX and ends in A,B,C,D,or E
        else if data(i).layers==3 &&
isempty(regexp(data(i).material,'GAX[ABCDE]','once'))==0;
                if data(i).drop==1 && strcmp(data(i).material,data(i-
1).material)==0
                    f=f+1;
                end
                foams(n,f-1)=data(i).peak/1000;
                fl{f-1}=data(i).material;

                if strcmp(data(i).material,'GAXA')  % If GAXA, also save to
configurations matrix
                    if data(i).drop==1 && strcmp(data(i).material,data(i-
1).material)==0
                        c=c+1;
                    end
                    config(n,c-1)=data(i).peak/1000;
                    cl{c-1}=data(i).material;
                end

                % For optimal foams GAXD and GAXE, replace peak force value
                % from single drop with median peak force from repeated
tests
                if strcmp(data(i).material,'GAXD')
                    foams(n,f-1)=GAXDmedian(data(i).drop)/1000;
                end

                if strcmp(data(i).material,'GAXE')
                    foams(n,f-1)=GAXEmedian(data(i).drop)/1000;
                end

            % Save all other samples to configurations matrix
            else
                if data(i).drop==1 && strcmp(data(i).material,data(i-
1).material)==0
                    c=c+1;
                end
                config(n,c-1)=data(i).peak/1000;
                cl{c-1}=data(i).material;

                % For optimal material GAXAAX, replace peak force value
                % from single drop with median peak force from repeated
tests
                if strcmp(data(i).material,'GAXAAX')
                    config(n,c-1)=GAXAAXmedian(data(i).drop)/1000;
                end
            end
        end
    end
end

% Save sorted peak force values to file for reference
gT=table(gel);
writetable(gT,'gelpeaks.xlsx');

iT=table(isoblox);
writetable(iT,'isobloxpeaks.xlsx');

fT=table(foams);
```

```
writetable(fT,'foampeaks.xlsx');

cT=table(config);
writetable(cT,'configpeaks.xlsx');

% Plot gelatine graph
figure;
a=bar(gel);
title('Peak Forces for Isolated 10mm Gelatine Samples','fontsize',16);
xlabel('Successive Drops','FontSize',14);
ylabel('Force (kN)','FontSize',14);
ax=gca;
ax.YAxis.Exponent = 0;
ax.FontSize=12;
grid on;
legend(a,gl,'location','NorthWest');

% Plot Isoblox compositions graph
figure;
b=bar(isoblox);
title('Peak Forces for Different Isoblox Compositions','fontsize',16);
xlabel('Successive Drops','FontSize',14);
ylabel('Force (kN)','FontSize',14);
ax=gca;
ax.YAxis.Exponent = 0;
ax.FontSize=12;
grid on;
legend(b,xl,'location','NorthWest');

% Plot foam types graph
figure;
c=bar(foams);
title('Peak Forces for Different Foam Types','fontsize',16);
xlabel('Successive Drops','FontSize',14);
ylabel('Force (kN)','FontSize',14);
ax=gca;
ax.YAxis.Exponent = 0;
ax.FontSize=12;
grid on;
legend(c,fl,'location','NorthWest');

% Plot layer configurations graph
figure;
d=bar(config,'FaceColor','flat');
title('Peak Forces for Different Layer Configurations','fontsize',16);
xlabel('Successive Drops','FontSize',14);
ylabel('Force (kN)','FontSize',14);
ax=gca;
ax.YAxis.Exponent = 0;
ax.FontSize=12;
grid on;
legend(d,cl,'location','NorthWest');
```

H.3 DataProcessor_ForceTime.m

```
% DataProcessor_ForceTime - ENGR9700 Masters Thesis
% Optimisation and impact assessment of
% novel protective guards used in cricket
%
```

```
% - Imports F vs. t drop test data from SignalExpress .csv files
% - (Data collected at sampling rate of 5kHz)
% - Extracts material name from file
% - Shifts data to align peak with t=0
% - Plots F vs. t profile with labelled peak force
%
% - File naming system:
% - [material][samplenumber].[repeat]_[date]
% - Refer to Appendix F for material labelling key
%
% An Lam, 2019

close all; clear all;

% Load all .csv files in this directory
fn=dir('*.csv');

% Counter for number of files
count=0;

% Create cell array to contain file names
fnam=cell(length(fn),1);

if isempty(fn)                      % If  directory does not contain .csv files
    fnam=[];
else
    for i=1:length(fn)              % Retrieve file name and remove '.csv'
        fnam{i}=getfield(fn,{i,1},'name');  % Extract file name
        fnam1{i}=fnam{i}(1:end-13);         % Remove extension and
unnecessary characters

        % Link file names to counter variable to allow for data plotting
        count=count+1;
        fnam2{count}=fnam1{i};
    end
end

figure;
freq=5000;                  % Sampling rate of 5kHz
period=1/freq;
rise=500;                   % Estimate of rise time frame
fall=4000;                  % Estimate of fall time frame (including bounces)
offset=rise*period;         % Set offset to align peak with t=0

for i=1:length(fnam2)
    % Import time and force data
    data=csvread(fnam{i});

    % Assign force data
    force{i}=data(:,2);
    F=force{i};

    % Find magnitude and index of peak force
    peakforce(i)=max(F);
    peaktime(i)=find(F==peakforce(i));

    % Remove excess data before and after peak
    F(peaktime(i)+fall:length(F),:)=[];
    F(1:peaktime(i)-rise,:)=[];
```

```
    % Create time vector of equal length
    l=length(F);
    time=-offset:period:(l-1)*period-offset;
    t=time.';

    % Plot force vs. time profile
    subplot(2,1,i);
    plot(t,F/1000);     % Convert N to kN
    ylim([-1 20]);

    name=fnam1{i};
    title(sprintf('Force vs Time for Sample %s', name),'fontsize',12);
    xlabel('Time (s)','FontSize',14);
    ylabel('Force (kN)','FontSize',14);
    ax=gca;
    ax.FontSize=14;
    grid on;
    hold on;

end
```

Appendix I: Full data set of peak forces for all samples

Table 19: Peak forces recorded for all samples (1 of 2)

Sample	Drop	Peak Force (N)
G2	1	4060
G2	2	4580
G2	3	5230
G2	4	5450
G2	5	5447
G3	1	854.8
G3	2	4545
G3	3	5397
G3	4	5278
G3	5	5135
G4	1	1013
G4	2	4027
G4	3	5118
G4	4	5499
G4	5	5148
G5	1	936.2
G5	2	1127
G5	3	751.7
G5	4	644.7
G5	5	681.6
GAR1	1	8853
GAR1	2	13826
GAR1	3	19039
GAR1	4	19243
GAT1	1	12744
GAT1	2	13794
GAT1	3	14006
GAT1	4	14117
GAT1	5	14185
GAX1	1	10406
GAX1	2	12632
GAX1	3	15239
GAX1	4	16679
GAX1	5	19014
GAZ1	1	6811
GAZ1	2	7486
GAZ1	3	7655
GAZ1	4	7325
GAZ1	5	7698

Sample	Drop	Peak Force (N)
GAXA1	1	10074
GAXA1	2	10966
GAXA1	3	11187
GAXA1	4	11653
GAXA1	5	11683
GAXB1	1	8870
GAXB1	2	10426
GAXB1	3	11021
GAXB1	4	10952
GAXB1	5	10986
GAXC1	1	9533
GAXC1	2	10953
GAXC1	3	11847
GAXC1	4	11532
GAXC1	5	12151
GAXD1	1	6445
GAXD1	2	7513
GAXD1	3	7458
GAXD1	4	7663
GAXD1	5	8152
GAXD2	1	6495
GAXD2	2	7248
GAXD2	3	7945
GAXD2	4	8247
GAXD2	5	8211
GAXD3	1	6706
GAXD3	2	7708
GAXD3	3	7744
GAXD3	4	8182
GAXD3	5	8063
GAXE1	1	6815
GAXE1	2	7583
GAXE1	3	7715
GAXE1	4	7868
GAXE1	5	7746
GAXE2	1	6440
GAXE2	2	7441
GAXE2	3	7643
GAXE2	4	7747
GAXE2	5	7605

Table 19: Peak forces recorded for all samples (2 of 2)

Sample	Drop	Peak Force (N)
GAXE3	1	5852
GAXE3	2	7029
GAXE3	3	7220
GAXE3	4	7487
GAXE3	5	7798
GAXX1	1	10064
GAXX1	2	10684
GAXX1	3	10768
GAXX1	4	10864
GAXX1	5	10079
GAXAX1	1	8817
GAXAX1	2	9757
GAXAX1	3	9941
GAXAX1	4	10185
GAXAX1	5	10371
GAXXA1	1	8631
GAXXA1	2	9916
GAXXA1	3	10388
GAXXA1	4	10331
GAXXA1	5	10296
GAXAAX1	1	6302
GAXAAX1	2	7677
GAXAAX1	3	7918
GAXAAX1	4	8519
GAXAAX1	5	8553
GAXAAX2	1	7127
GAXAAX2	2	7787
GAXAAX2	3	7746
GAXAAX2	4	7886
GAXAAX2	5	7803
GAXAAX3	1	7326
GAXAAX3	2	7605
GAXAAX3	3	7875
GAXAAX3	4	7982
GAXAAX3	5	7853
GAXAXX1	1	7308
GAXAXX1	2	8651
GAXAXX1	3	9339
GAXAXX1	4	9313
GAXAXX1	5	9261