Representative testing of personal protection equipment

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Representative Testing of Personal Protective Equipment

by

Paul Walker

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Loughborough University

May 2014

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Abstract

The purpose of the work reported within this thesis was to design and implement a series of tests which better replicate the impact conditions experienced during a game, and allow for quantitative measurements of performance of various items of personal protection equipment (PPE). The sports of cricket and taekwondo were used as case studies. The aim was to improve on existing testing protocols making them more representative of real life, an approach that has not been previously attempted in the literature and so required design of multiple items of novel equipment.

A representative cricket impact test was developed utilizing a ball cannon firing a cricket ball mass at an equivalent bowling velocity of 31 m/s (70 mph) and a novel, freely suspended force acquisition system with embedded accelerometers from which the transmitted force values could be derived. Throughout the testing secondary variables of coefficient of restitution (COR), deformation and contact time were measured from high speed video footage to give further insight into the impact mechanics of the three tested leg guards. Contact times were in the range of 3 ms - 4 ms, COR between 0.38 - 0.50 and deformation between 45 mm - 52 mm. These results were compared against other benchmark tests to establish how close the representative test was to an actual human related ball-pad impact and to estimate human tolerance levels to impact.

A rig to mimic a human on human kicking impact in taekwondo was designed to measure performance of the piece of body protection equipment used in training and competition, commonly referred to as a hogu. Primarily a mechanical simulator was designed to replicate the speed and mass of a human leg impacting during a roundhouse kick. A force acquisition system was manufactured, capable of integrating with the kicking robot functioning, with a human torso sized and shaped anvil, using a similar accelerometer based system of force measurement as that introduced in the cricket testing. This test was then used to measure performance levels of nine off-the-shelf hogus and protective training pads. Using transmitted peak force and time to peak force (TTPF) as indicators of protection, these values were found to range from between 0.5 kN – 7.5 kN and 9 ms - 23 ms across the pads indicating a major difference in the protection provided.
Acknowledgements

I want to thank everyone for their support throughout the lengthy period of my research. Thanks goes to my numerous supervisors, Dr Andy Harland who has been here throughout, and the others who I witnessed their departure, Prof. Roy Jones, Dr Chris Holmes & Dr Dan Price. Thank you for the help, the advice and mostly the understanding that I’d rather be pole vaulting so won’t be sat at my desk every day. Thanks also to the numerous members of the SCUTA project, to Prof. Richard Hague for leading the project and providing many a free lunch, and to the lads, BC, Webster and Felix whose company managed to brighten many a dull meeting.

I would like to thank many members of the Sports Technology Research Group, who have all been available to provide advice and direction when requested, but in particular the work horses of the department, Steve Carr, Andrew Hallam and Simon Neil. Without their technical manufacturing skills my thesis would have become a philosophy of personal protection equipment testing protocols.

Thank you also should go to my many friends throughout the project, many of whose incessant questioning, “are you a doctor yet?”, provided a constant reminder that I really should get back to work.

Finally the biggest scoop of gratitude is reserved for my parents without whose provision of patience, support and genetic material I would not have been able to achieve what I have in any part of my life.
Publications


"I love the pole vault because it is a professor's sport."

Sergey Bubka
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**Nomenclature**

BOB - Body Opponent Bag
BS - British Standard
BTCB - British Taekwondo Control Boards
COR - Coefficient of restitution
FIFA - Fédération Internationale de Football Association
ISA - The International Standards Authority
ITF - International Taekwondo Federation
LDV - laser Doppler vibrometer
NOCSAE - National Operating Committee on Standards for Athletic Equipment
PPE - personal protection equipment
TTPF - time to peak force
WTF - World Taekwondo Federation

\( a \) - acceleration \((m/s^2)\)

\( a_x, a_y, a_z \) - subscript denotes axis direction

\( a_1, a_2, a_3 \) etc. - subscript denotes referred object

\( a_b \) - acceleration of ball

B - calculation constant

\( b \) - breadth \((m)\)

c - damping coefficient \((Ns/m)\)

c_f - damping coefficient of foam

d - depth \((m)\)

e - coefficient of restitution

\( E \) - Young’s Modulus \((N/m^2)\)

\( E_e \) - effective kinetic energy \((J)\)

\( E_k \) - kinetic energy \((J)\)

\( f \) - frequency \((Hz)\)

\( f_n \) - natural frequency in hertz

\( F \) - force \((N)\)
<table>
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<tr>
<td>$F_{\text{max}}$</td>
<td>maximum force</td>
</tr>
<tr>
<td>$I$</td>
<td>area moment of inertia</td>
</tr>
<tr>
<td>$k$</td>
<td>stiffness</td>
</tr>
<tr>
<td>$k_t, k_i, k_p$</td>
<td>subscript denotes referred object</td>
</tr>
<tr>
<td>$l$</td>
<td>total length or thickness</td>
</tr>
<tr>
<td>$l_{\text{cm}}$</td>
<td>distance to centre of mass</td>
</tr>
<tr>
<td>$M$</td>
<td>Moment</td>
</tr>
<tr>
<td>$m$</td>
<td>mass</td>
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<tr>
<td>$m_1, m_2$</td>
<td>subscript denotes referred object</td>
</tr>
<tr>
<td>$m_b$</td>
<td>Mass of ball</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Effective mass</td>
</tr>
<tr>
<td>$r_x, r_y, r_z$</td>
<td>rotational acceleration, subscript denotes axis</td>
</tr>
<tr>
<td>$T$</td>
<td>period</td>
</tr>
<tr>
<td>$t$</td>
<td>impulse time</td>
</tr>
<tr>
<td>$t_{\text{den}}$</td>
<td>densification time period</td>
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<tr>
<td>$u$</td>
<td>inbound velocity</td>
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<tr>
<td>$u_1, u_2$</td>
<td>subscript denotes referred object</td>
</tr>
<tr>
<td>$v$</td>
<td>outbound velocity</td>
</tr>
<tr>
<td>$v_1, v_2$</td>
<td>subscript denotes referred object</td>
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<tr>
<td>$x$</td>
<td>displacement in x-direction</td>
</tr>
<tr>
<td>$x_0, x_{-1}$</td>
<td>subscript denotes time step or referred object</td>
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<tr>
<td>$y$</td>
<td>displacement in y-direction, from centreline</td>
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<tr>
<td>$\alpha, \alpha'$</td>
<td>defined relative coordinates system</td>
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<td>density</td>
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<tr>
<td>$\sigma$</td>
<td>stress</td>
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<tr>
<td>$\tau$</td>
<td>impact duration</td>
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(单位)
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<th>Symbol</th>
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</tr>
<tr>
<td>$\omega_d$</td>
<td>damped frequency</td>
<td>(rads)</td>
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1. Introduction

This chapter introduces the thesis as a whole and outlines the need for why this work is being carried out. Research reported in this thesis was carried out as part of a larger project, known as SCUTA, which is introduced and this body of work is laid out into that larger context, the candidate sports are introduced along with the items of personal protective equipment (PPE) to be investigated and some of the injury mechanisms that they will need to protect against. A brief introduction to some of the materials used in PPE is also given and some of their characteristics explained. Overall this chapter gives an introductory background to the project as a whole whilst defining the specific aims to be achieved.

1.1 Background

Increasing professionalism and ever-improving training regimes continue to lead to an increased performance in all areas of sport. With the growing speed, strength and technique of the athletes involved there is a danger that injury risk may increase. It is important that the personal protection equipment used in each sport is able to provide the required protection and yet still allow the players to perform to the highest level. With traditional PPE being bulky and cumbersome, and in some circumstances detrimental to player performance, a range of custom-fitted, light weight and slim-line PPE would allow players to move more freely whilst remaining protected.

The SCUTA (Latin for shield) project was started to achieve these goals. The aim was to create a new system of PPE for cricket and taekwondo competitors utilising additive manufacturing. A scan of the participants body part would allow a designed protective structure to be mapped to their body surface giving a new level of customisation and fit, with each item of PPE being individually manufactured using additive manufacturing. This was an integrated project with six work packages in total, 5 of which represented PhD studies. Figure 1.1 shows a visualisation of the six work packages working together to address the project aims. A brief introduction to each work package is given below along with explanations of how the separate areas feed into each other.
Figure 1.1 – Spider diagram of the six SCUTA work packages

**Instrumentation** – This work package was aimed at developing methods to automate the scoring system used in taekwondo in order to remove the subjective component of the current judicial system.

**Biomechanics of Impact** – This work package studied the mechanisms of injury in the studied sports and attempting to establish measurable values for different types of injury due to impact. The results of this study were important for both the Instrumentation and Testing Protocols work packages (Tsui, 2011).

**Comfort Testing and Player Protection** – This work package considered which factors affected comfort for the players and how the players perceived the current PPE, this was important so that a new product would be accepted by players (Webster, 2010).

**Surface Conformity and Structure** – This work package dealt with the design of a protective structure, how this would fit into a garment and mapping this structure to scan data in order to create the garment. The protective performance of the garment is dependent on both the structure and materials used so these two work packages were very closely linked.

**Materials** – The aim of this work package was to research new materials and to develop their usage in additive manufacturing machines, this was required as available materials at the commencement of the...
project had been developed for creating prototype models, not for mechanical performance. This was the only package without a PhD study attached.

**Testing Protocols and Benchmarking** – This work package was tasked with creating a series of new testing protocols which better represented the game situations that the PPE would be used under and using these testing regimes to benchmark the current levels of protection provided. This work package required input from both the biomechanics of impact and the player perception package, and its results were used to guide the design of the protective structure of the garment and the materials used to build it.

The reason for developing tests representative of the game situations within which PPE would be used is linked to the development of a new system of constructing the protective structures of the garment. Using the proposed system of additive manufacturing to custom make individualised PPE garments, it is also possible to fine tune the structural make-up of the protective aspect of the garment in order to optimise the protection levels for different positions on the body. A test that is as close to the functional game situation as possible is needed to allow this optimisation to be for the correct loading characteristics. By using a realistic test to benchmark currently available PPE garments, actual performance of current garments can be analysed and the overall protective success of future manufactured garments can be seen.

The testing protocols developed within this work will be attempting to achieve a compromise between realism and repeatable material tests. A truly realistic test may need to sacrifice repeatability and measurement accuracy in order to accurately reproduce all aspects of the impact which occurs during a game situation, and similarly current materials style testing protocols limit the specificity of the impact to generate a much more repeatable test capable of accurately measuring performance under controlled conditions. The aim of the work throughout this thesis is to generate tests that can more closely represent the impacts occurring during a game situation whilst still maintaining the accuracy of measurement and repeatability required, to be considered a useful testing protocol.

### 1.2 The Candidate Sports

This project will be focusing on two candidate sports, namely cricket and taekwondo. With cricket leg guards and taekwondo hogus being the focus PPE garments respectively. The reason for the selection of these sports, and in particular these garments, as the examples used within this thesis relate to the difficulty of
modelling the boundary conditions of a representative impact. The process for developing a representative test for each will differ for the two sports due to numerous factors, including, amount of previous research having been carried out that can provide starting points, availability of equipment to recreate impacting conditions, suitability of force measurement systems and also the complexity of the impact being modeled. As a result the approach to developing each test may be significantly different but will be achieved by applying the same principles.

There has been minimal change in the appearance of the cricket leg guard since the early playing days, as highlighted by figure 1.2, which depicts W. G. Grace playing cricket in 1883. The same basic design and features can be seen in figure 1.3, which illustrates a cricket leg guard sold and used by many players throughout the world. The main features of a traditional leg guard are highlighted and explained below.

Figure 1.2 – W. G. Grace playing cricket in 1883 (Probert, 2014)

Figure 1.3 – A modern day cricket leg guard with the important features highlighted
Shin Protection – this forms the majority of the pads surface, providing flexibility perpendicular to its long axis to allow it to wrap around a player’s leg. Longitudinal canes provide resistance to bending in that direction and help distribute the force of impact.

Longitudinal rolls – These are formed as a by-product of the cane-based protective structure though are often replicated in non-cane pads too. Each “roll” contains a single cane, and in modern designs these are also filled with various padding materials that absorb force and dissipate energy.

Knee Rolls – Lateral rolls of padding which protect the knee. These are constructed using similar, but often greater amounts of padding as the vertical contours but do not contain a cane and so have much lower resistance to bending.

Thigh Protection – The section of the pad that extends above the knee. This gives protection to the lower thigh and also prevents balls striking the top of the knee when in a deep bend.

During the impact occurring with a cricket leg guard, a cricket ball with a given velocity impacts the players’ lower leg, which is protected by the leg guard. The boundary conditions of the ball are easily measured by taking the mass, size, velocity and stiffness of the ball, and thus should be relatively easily replicated. Although the stiffness of the lower leg of the player is more difficult to quantify, it is relatively fixed throughout the impact. This example of a ball-on-human impact seems initially relatively simple to model and should allow a fairly close representation of the in-game conditions during a measurable test.

Within taekwondo there are many different governing organisations throughout the world, each with slightly differing rules conducting how combat should be carried out. The biggest two are the International Taekwon-Do Federation (ITF) and the World Taekwondo Federation (WTF). The WTF philosophy is that under tournament conditions all combat is full contact and by executing techniques at full force this simulates a real fight as closely as possible. It is this desire for full contact that necessitates the use of a hogu or body protector to protect the competitors from serious injury. WTF rules are used during competition at the Olympic Games. In ITF tournaments the techniques are not allowed at full force and as such a hogu is not a
requirement. Figure 1.4 below shows a standard taekwondo hogu. Under WTF rules competitors must also wear a groin guard, shin and forearm guards and hand protectors along with a mouthpiece.

Most hogus have a similar shape to the one shown in figure 1.4. They have a small amount of protection for the shoulders and the two side panels then bend around the competitor and are secured at their back with either ties or Velcro attachments. Each bout requires a competitor wearing red to fight a competitor wearing blue, so most hogus are reversible, with one side red and one side blue so they may be used for either competitor during a tournament. The hogu is designed to give protection to the body whilst allowing freedom of movement for the arms and legs about the shoulder and hip joints.

The hogu also serves the purpose of designating the scoring areas during a contest, from the official WTF rules the area between the armpit and pelvis covered by the hogu is the legal attacking area, this is also the part of the hogu which is coloured either red or blue. Attacks to the spine are not allowed. Scoring attacks should be delivered accurately and powerfully, a scoring blow should be delivered to the correct region with enough force that the opponent's body is abruptly displaced by the impact. Punching and kicking techniques are allowed to the body but only a kick may score to the head. Tournaments are split up into weight categories so the force and pressure applied for a scoring blow in a lightweight category will not be the same as that required to score in one of the heavier classes. The size of the hogu worn is related to the athlete’s height, so a taller athlete is required to wear a larger hogu and thus his scoring area is larger (WTF, 2009).
Taekwondo was chosen to represent a much more complex impact to model. When a human kicks another human, the biofidelity of both sides of the impact must then be approximated, leading to a much more challenging set of bounding conditions. There are multiple kicks that can be performed in taekwondo, each will produce differing force profiles and impact in different positions. Even the same kick by different competitors will differ due to limb length, mass, relative strength and joint stiffness of the competitors’ leg. Similarly on the other side of the impact, the mechanical properties of a human torso vary with position and depend on the level of muscular contraction, within a taekwondo bout it is also far more likely a competitor may be moving either into or away from a kick. This human-on-human impact represents a much more complex system to represent in a testing protocol.

The choice of the candidate sports was based on having one simpler impact to model and one more complex. The choice of one ball-on-human and one human-on-human impact mean that the protocols and test given here can be more easily adapted to cover any other sport as all protective equipment is designed to protect a human from the impact of either an implement or another human. This gives the project a global application as a starting point for development of any other required testing protocols.

1.3 Impact and Injury

Injuries in sport are typically the result of overuse and/or acute overload (McIntosh, 2005). Acute overload injuries occur in sports such as ice hockey, American football and lacrosse where high mass, high velocity body to body collisions occur or through low mass, high velocity object to body impacts (Caswell and Deivert, 2002). Although a full analysis of the possible injuries and their mechanisms within the focus sports is beyond the scope of this project a brief overview will help to build understanding of the causes of injury and how these can be avoided. This knowledge will help with further development of PPE garments and could be used to specialise their design to reduce risk of certain injuries. For the purposes of this project an injury is defined as having occurred any time a player’s acceptable pain threshold is exceeded so as to cause distraction from the game/match.

In the case of cricket, the major injury concern with inadequate leg guards would be that of contusion. Soft tissue contusions, or bruising, are caused by localised damage to blood vessels leading to a leakage of
blood into extracellular spaces (Cavanaugh et al., 1986). The majority of contusions results from muscle and other tissues being compressed against the bone (Walton & Rothwell, 1983) so in the case of a cricket leg guard this would be the ball impacting the soft tissues and compressing them against the tibia bone, this would also suggest that a contusion would be more likely in an area with less soft tissue overlying the bone. Although there is little literature dealing with contusions to the lower legs, several papers cover thigh protective pads which are used for similar reasons, Aronen et al. (2006) stated that protective thigh pads provide a dual purpose, they are worn in the hope of reducing the incidence and severity of injury as well as protecting a recently injured area from further injury. The severity of contusions can vary greatly but work by Ryan et al. (1991) stated that the majority of thigh contusions are not serious but they do cause performance impairment and time away from activity. Overall, the aim of the cricket leg guard would be to protect against contusions either by removing enough energy from the incoming ball that soft tissues are not sufficiently compressed, by spreading the load applied by the ball over a greater area or a combination of the two.

In taekwondo, the hogu protects both the chest area and the abdomen. The rib cage forms a rigid protective structure with little overlying soft tissue to protect the most important internal organs in this region; the abdomen on the other hand is predominantly muscle tissues with no bony structures for protection. Despite these differences Viano et al. (1989) discussed both areas together stating that serious abdominal and thoracic injury from high speed lateral impact may be associated with a rapid phase of compression. King (2000) made a clearer distinction reporting that chest trauma is especially dangerous due to the vital organs located in this area. He distinguished between “blunt” and “penetrating” impacts depending on the energy and velocity of impact. In terms of a taekwondo kick, these would fall into the medium velocity impacts (3 m/s – 30 m/s), an area where viscous injuries become the most prominent. A viscous injury occurs when a fluid filled organ is compressed quickly, for example by a shock load, tissue does not have time to deform and organ rupture may result even in the absence of large degrees of deformation. This can lead to internal injuries in the absence of any skeletal damage. In contrast the abdomen has no rigid rib structure so blunt impacts to this region will be more likely to cause higher deformations, compressing underlying organs.

This dangerous compression can cause enough pressure to burst or rupture organs or possibly stretch or tear more ligamentous structures (Tsui, 2011). Regarding an ideal hogu, the purpose of the thoracic region would be to reduce the transfer of kinetic energy to internal organs whereas over the abdomen a more rigid structure to prevent larger penetrative deformations would be more desirable.
From this simple analysis, it has been shown that there is a difference within the requirements of PPE garments for each of these sports in terms of protection afforded and body parts being protected, thus this distinction is reflected in their design.

1.4 Aim of the Project

The aim of this project is to develop a series of testing protocols, using cricket leg guards and taekwondo as the case studies, which better represent the impact conditions that are encountered during a game situation. These tests, whilst being representative, should still quantitatively measure performance in a repeatable manner. This means moving away from traditional material testing protocols and establishing tests that measure garment performance but replicate loads, impacts and other boundary conditions that would be experienced during a game.

The aim is to quantitatively measure and compare either one or several variables between several garments of PPE to establish benchmarks and a hierarchy of performance. Tsui (2011) reports that numerous variables have been linked with study of injury mechanism, some are: force, rate of force development, deformation, rate of deformation, contact time, pressure, energy absorption and/or rate of energy absorbed. Current testing regimes (BS 6183-1:2000, etc.) use peak force values to establish protection levels of PPE, it was suggested by Tsui (2011) that pressure may be a better indicator for injury especially in the case of contusions. The difficulty of measuring pressure throughout an impact has been demonstrated by Pain et al. (2008) when using the TekScan system. Tekscan is a thin film system for measuring pressure generally used for recording foot strike data, which was adapted in Pain’s work to measure the impact pressures during rugby tackles. The two main problems for this type of work are that the sensors method of multiplexing data within a long sampling window (4 ms) and also the low dynamic response time may have caused the total impact peak force to be missed, this lead to errors and highlighted the importance of sampling rate. This issue of sampling rate was relevant for all dynamic pressure measurement devices on the market at the start of this project, and as a result, for both simplicity and accuracy force measurement has been chosen as the variable indicative of protection, a lower peak value and slower time to develop indicating a more protective garment. This gives justification to also testing on anvils with simple geometries, by doing so pressure distribution is likely to be fairly predictable across the impact area.
In summary, there are two main aims of this project:

- Develop a representative test for cricket leg guards, capable of measuring transmitted force under impact conditions replicating those experienced during a match
- Develop a representative test for taekwondo hogus, capable of measuring transmitted force under impact conditions replicating those experienced during a match

The attempt to create testing protocols that measure performance under conditions replicating those found in a game situation represents a novel area of investigation. Additional objectives will be to use these tests to benchmark currently available items of PPE and also to establish quantitatively how closely these tests represent the impacts occurring during the game. The measurement of transmitted force will be used as an indicator to the potential for injury, a higher transmitted force indicating a higher potential for injury and thus a lower level of protection.

### 1.5 What is Representative Testing?

The British Standards lay out the current testing protocols used to establish minimum performance levels for items of PPE. They use a series of drop-test scenarios to carry out dynamic testing of the various garments. The designers of these tests have tried to match the kinetic energy of their tests with that of the expected in-game impacts. This may be acceptable for materials that respond to impacts independent of speed, but the foams used in modern PPE are highly strain rate dependent. It is important to consider more than just the energy of the impact. By controlling the mass and velocity of the bodies involved in the impact, these can be set to mimic the in-game situation. By replicating masses and velocities of the impact, both the momentum and energy of the collision are also controlled and should give an accurate replication of the required force time curve. In a game of cricket, the cricket leg guard protects the wearer from the relatively light cricket ball being projected at high velocity towards the wears shin and knee regions and thus a testing protocol using a cricket ball mass moving at the same speed as a bowler would deliver the ball may be considered more representative.
In order to truly represent any impact with PPE, such as the leg in the case of cricket, it is necessary to create an anvil mimicking the characteristics of a human leg upon which to measure the transmitted force, an anvil that matches these characteristics exactly would be termed biofidelic. There are several issues related to using this type of anvil, it becomes difficult to measure forces accurately, measurements then include mechanical responses from both the pad and the leg model and mechanical response of the anvil itself is liable to change over time and repeated testing. The final design will be a compromise between a true mechanical material test and 100% biofidelity.

The effect of an impact on a deformable body has been widely studied in the literature, it has been shown several times that when a rigid mass impacts a deformable surface, the mechanical response is dependent on the mass of the object, contact area and impact velocity (Nigg & Yeadon, 1987, Martin et al. 1994). These experiments however have concerned themselves with just the one deformable body, Pain et al. (2008) when referring to rugby shoulder pads stated that during game situations the padding is sandwiched between two sets of non-linear viscoelastic bodies. The net effect of the padding is dependent on the resultant viscoelastic properties of the whole system and the total energy imparted during impact. Ideally for padding to be effective and offer maximum protection, it needs to be tuned to the specific task it aims to defend against; that is, the padding needs to be tested under realistic loading regimes. The hypothesis was backed up by showing that rugby shoulder pads were only effective at mitigating peak force values from stiffer impactors, i.e. they were effective during materials type testing but less so in a “game” situation. Milburn et al. (2001) also showed that the choice of impactor had a direct influence on the impact mitigating performance of the shoulder pad. Using a medicine ball to better represent soft tissue than the rigid ‘hammer and anvil’ type tests, it was found that IRB-approved shoulder pads did not provide significant force reduction. With regards the testing already carried out Hrysomallis (2009) reported that both the basic curved steel anvil used in assessing protective cricket equipment and the lower limb of the Hybrid III crash test dummy are both examples of physical leg models but neither of these have been designed to measure the soft tissue response to impacting blows.

Although the research shows that to establish true human tolerance levels for impact, the biofidelity of the anvil and possibly the impactor are important, this is not the purpose of this work. The benchmarking of PPE under game-like conditions can be performed without this requirement of biofidelity as relative comparisons between garments under repeatable test conditions are equally useful. Were human tolerance data already
available then a biofidelic test would allow direct comparison of human and test data, but in their absence matching the energy, momentum and strain rates of game impacts will provide sufficient for a representative test. The pre-impact energy and momentum of the impactor are both determined by its mass and velocity, thus controlling these variables provides a starting point for a representative test.

1.6 Strain-rate Dependency

The main importance of specific testing protocols, highlighted within this work, is the relevance of strain-rate. The primary component of the tested PPE garments is the various foams used to spread and absorb the impact forces. Within the literature the strain-rate dependence of these foams has been demonstrated over and over. A prime example being the work of Davies & Mills (1999) working specifically on the Confor foams used in the design of the custom hogu tested in Chapter 9. They demonstrated the strain rate dependence of these foams and noted that the maximum rate effect was seen between 1 m/s and 10 m/s. This effect has also been demonstrated on a range of other foams under different testing protocols.

Subhash et al. (2006) tested both low density (<1000 kg/m$^3$) and high density (>1000 kg/m$^3$) foams under quasi-static and high strain rate conditions. For both foams the failure strength increased but strain to failure decreased. They also showed that the higher the density of the foam the higher the strain rate sensitivity of failure.

Saha et al. (2005) describe how the typical stress-strain response of foams will show four typical stages of deformation, these being elastic behaviour up to peak stress, post-peak softening, plateau and densification. For cellular solids, the elastic behaviour up to peak stress is controlled by the elastic bending of cell walls whereas the post-peak softening is associated with plastic bending. The plateau stage is then caused by the collapsing of cells after their walls have bent plastically. After most cells have collapsed opposite cell walls can touch each other and cause the densification stage where stress levels begin to rise again rapidly. Examples of the resultant stress-strain profile can be seen can be seen in figure 1.5 adapted from their paper.
In their work, they found that at increasing quasi-static strain rates (0.001 s\(^{-1}\) - 0.1 s\(^{-1}\)) both peak and plateau stress increased. At higher strain rates (130 s\(^{-1}\) - 1750 s\(^{-1}\)) the stress-strain responses are very similar up to the post-peak softening region. Initial slopes of the stress-strain curve were found to be steeper at high strain rates and increases in the peak stress were also found. They showed that peak stress and energy absorption are strongly dependent on strain rate, density, microstructure and foam material. Rate dependent behaviour is found to be more pronounced for higher density foams. Chen et al. (2007) found similar results stating that peak stress is strain-rate sensitive and depends on the square of the foam density, similarly Mae et al. (2008) showed that elastic modulus, yield stress and rupture strain are strongly dependent on the strain rate and density.

Ouellet et al. (2006) noted that although polymeric foam materials are widely used for impact protection and energy absorption, most data available in the literature only addresses strain rates of up to 250 s\(^{-1}\). They looked at three common polymeric foams at strain rates from 0.0087 s\(^{-1}\) up to 2500 s\(^{-1}\), maintaining high degrees of compression. They found that there were relationships between stress and strain rate up to approximately 1000 s\(^{-1}\), but beyond this critical value the relationship becomes distinctly non-linear.

This difference in performance shown by polymeric foam materials at differing strain rates is the driver behind the requirement of this thesis to devise a series of representative testing protocols. By refining the testing process so that the impacts are carried out at the same strain rate as those encountered during a game situation, then the true performance of these garments can be measured rather than using a test that approximates it.
1.7 Polymer Foams

The analysis of polymer foams is a wide and general topic, but this work will focus on their use in protective equipment. The choice of foam for a particular purpose will be made depending on the requirements of a protective garment as well as cost, availability and ease of processing. Even within one item of protection equipment, several foams may be used in combination to achieve a particular purpose or goal.

![Open-cell foam micro-structure](image1)

*Figure 1.6 – Open-cell foam micro-structure (Nasa, 2009)*

![Closed-cell foam microstructure](image2)

*Figure 1.7 – Closed-cell foam microstructure (polymers PPI, 2009)*

A distinction can be drawn between the properties of certain foams by considering their micro-structure. There are two main micro-structures to be considered, and these are open-cell (figure 1.6) and closed-cell foams (figure 1.7). The open-celled foams are so-called because they are constructed from individual cells,
which have either incomplete, or no cell walls giving them a lattice-like appearance. These holes allow the passage of air easily between cells and allow the mechanical properties of the foam to be governed by the stiffness and buckling of the cell framework. Air-flow through open-cell foams usually does not contribute to the mechanical response (Mills, 2007). Each of the individual cells is variable in both size and shape but a set of three rules, proposed by Williams (1968), which describe the “average cell” can be used to approximate a regular structure. The rules are:

1) The average number of faces per cell is close to 14
2) The average number of sides per face is 5.1
3) The vertices, where 4 sides meet are nearly tetrahedral with inter-edge angles close to 109.5°

Previously Lord Kelvin (1887) showed space could be partitioned into identical tetrakaidecahedron cells of equal volume and minimal surface, this polygon most closely satisfies Williams conditions. This Kelvin cell, as it is also known, is a 14-sided shape constructed of both quadrilateral and hexagonal sides. This tetrakaidecahedron design has been analysed at high strain rates by Zhu et al. (1997), where theoretical models were developed for the reactions of the structure under loading and good agreement found with experimental results. It is this tetrakaidecahedron design that is proposed as the protective structure of the AM garments within the SCUTA project.

The closed-cell foams are so-called because each individual cell functions as an individually sealed unit. The properties of these foams are therefore dependent on both the structural properties of the cell walls, and the compressive qualities of the gas. The combination of the mechanisms makes these foams more difficult to model. Flexible closed-cell foams are used in the midsoles of trainers, these deteriorate over time due to gas loss diffusion out of the cells. Rigid closed-cell foams have predominant usage in safety helmet design.

In the design of PPE, it is possible to use just one, or a combination of foams to achieve a compromise between comfort and protective qualities as the foams themselves can serve several purposes. On the underside of a garment, softer foams are typically used to provide a comfortable fit to the garment, but in terms of protection there are two mechanisms by which the foams can reduce the transmitted force of an impact; the foams cellular structure itself can bend and deform and in doing so absorb energy, this absorption of energy is referred to as viscoelasticity. The foam can also be rigid enough to spread the load.
over a greater area (canes and solid plastics are also used for this purpose) thus decreasing the pressure of an impact and giving a greater area of foam over which the first mechanism can work.

The viscoelasticity of foams is one of the desirable characteristics that has lead to their wide-spread usage within PPE. Under loading and unloading, these materials display a hysteresis where the stress-strain curve for unloading falls below that of loading, figure 1.8. The arrows indicate the progression of the testing cycle. The entire area below the blue curve represents the energy input into the material during loading, and the area below the red curve is the energy returned on unloading. This leaves the area between the two curves as the energy lost from the cycle due to the viscous nature of the material. This dissipation of energy makes these foams useful for use in PPE as they reduce the energy of an impact, and thus the energy transferred to the human body and in turn reduce the potential for injury.

![Figure 1.8 – Graphical representation of hysteresis](image)

As well as hysteresis, viscoelastic materials also exhibit stress relaxation and creep. Stress relaxation is where a step increase in strain causes a decreasing stress value with time, and creep is a similar phenomenon where a step increase in stress causes an increasing strain with time. These responses are a result of the viscous nature of these substances.

The word viscoelastic comes from the two terms that describe the material properties as a combination of viscous and elastic. The elastic part describes the materials ability to be loaded and unloaded whilst returning to it original size and shape without permanent deformation, whereas the viscous part describes how there is a time delay in the response. A viscous material will resist strain when a stress is applied, leading to a lag between the stress and strain response of the material under dynamic loading. Simplified
models of viscoelastic materials have been developed using these principles. One of the most widely used is the Kelvin-Voigt model.

This model represents the material as an elastic spring of stiffness $k$, placed in parallel with a dashpot damper of damping coefficient $c$. When used, this model assumes a constant stiffness and damping ratio throughout impact, no analytical solution exists for a system where these values are allowed to vary throughout impact (Goodwill & Haake, 2001). This model has been used extensively in tennis ball impacts, and Neville (2001) showed that this simplified model predicted the balls displacement, velocity and acceleration about its centre of gravity with sufficient accuracy to validate this assumption. Using this model allows an analytical approach to be developed. For the system of a ball striking a foam placed on a rigid surface (shown in figure 1.9) the ball can be represented as a mass, $m_b$, and the foam by an idealised spring and damper system set up in parallel, $k_f$ and $c_f$, then the following series of equations can be formed:

$$F = -m_b \ddot{x}_b = c_f \dot{x}_b + k_f x_b \quad (1.1)$$

For the force, $F$, applied to a 1 m$^2$ area and the extension occurring over a 1 m length, we can use expressions for stress and for strain to write the following:

$$\sigma = E \varepsilon + \eta \frac{d\varepsilon}{dt} \quad (1.2)$$

Figure 1.9 – Kelvin-Voigt model of a ball impacting a rigidly supported foam
Where $E$ is the Young’s Modulus of the material and $\eta$ is the viscosity (Brach, 1991). This shows how the stiffness and damping given in the Kelvin-Voigt model can be related to the more traditional material variables such as stress and strain, and the Young’s Modulus. All elastic materials are viscoelastic to some degree, but commonly to such a small amount that their energy loss and/or hysteresis is unnoticed. It is the large degree of viscoelasticity that can provide the energy absorption required of PPE that makes foams ideal for this use.

1.8 Uncertainty

Due to the experimental nature of the work carried out within this thesis, a common theme throughout will be the identification of uncertainty within the results. In the context of this thesis, the uncertainty attributed to the results will be dependent on three main factors:

- The uncertainty due to inaccuracies of measurement equipment
- The uncertainty due to human error in analysis of video footage
- Whether the factors measured directly contribute to causing injury

Inaccuracies in measurement equipment are dealt with at various stages throughout the thesis. Due to the development of novel systems for measuring force, the uncertainty in this area is minimized through calibration of each new system using professionally calibrated force transducers. This is carried out in section 4.4 and section 8.5. When the results of measurements taken using this novel equipment are presented, the discrepancy between the measured values and the calibrated values are included as a measure of uncertainty.

High speed video footage is used as an adjunct to the force measurement throughout this thesis. The high speed video footage is manually analysed to measure secondary variables associated with the impacts. Due to the inherent uncertainty of human analysis, a thorough investigation into the uncertainty attached to this is carried out in section 3.6. The uncertainty of measuring these variables from video footage are then included whenever these results are presented throughout the thesis.
As discussed in section 1.4, the aim of this project is to measure transmitted force throughout impact as this has been used as a correlate for injury, a higher transmitted force being an indicator of higher potential for injury. It is also noted that pressure may be a better indicator of this. From a purely engineering stand point, it is difficult to quantify this, but not knowing a definitive injury causing criteria means there is an inherent unknown error in the experimental work. It is important to understand that this is a contributor to the uncertainty throughout.

1.9 Conclusions

This introductory chapter has now laid out the aims of this project and established a broader context for this in terms of the SCUTA project as a whole. The two focus sports have been introduced and the differences between the impact conditions to be protected from highlighted. The different injury mechanisms have also been discussed, and the reasons for the need for representative testing introduced, with a specific focus on the need to match the strain rates for the materials used within these items of PPE. A brief introduction to the currently used materials and the models used to represent them are given to create a foundation for the research conducted and a brief introduction to how uncertainty will be considered throughout the project is given.
2. Literature review

Sports injuries are some of the most common injuries in modern western societies, treating sports injuries can be difficult, expensive and time-consuming, and thus, preventative strategies and activities are justified on medical as well as economic grounds (Parkkari et al. 2001). It has also been shown that regulations mandating protective equipment reduce the incidence of injury (Marshall et al. 2002). Protective garments include, but are not limited to, helmets, shoulder pads, knee pads, thigh protectors, groin guards, shin guards and are used in many sports including hockey, cricket, football, lacrosse and many martial arts.

It was reported by Norman (1983) that the user expects that testing of the equipment has been conducted sometime during the prototype development or production process. Whereas in fact a great deal of the protective equipment used in sports has been developed on a trial and error basis with little, if any, objective laboratory evaluation of the degree of protection provided by the product.

The purpose of this literature review is to consider the injury rate in the focus sports and how this reflects on the PPE garments to be studied, to report on testing standards or methodologies that have been developed on the garments and to analyse the existing research in order to begin setting boundary conditions for proposed representative tests.

2.1 Cricket

2.1.1 Injury rates, types and mechanisms

The incidence of lower limb and knee injuries caused by the impact of the cricket ball have been considered previously. Stretch et al. (2000a) states that in addition to the technical skills required of modern batsmen, they must not only avoid direct injuries by ball strikes but also indirect and overuse injuries.

Cricket is unique of many sports in that there has been proposed a unified method for injury surveillance internationally (Stretch et al., 2005a). This was collaboration between cricket authorities in Australia, the United Kingdom, South Africa, New Zealand, the West Indies and India. It proposed a standard procedure for injury classification by severity and body part and stated definitions for the rates and time periods over which these should be measured and reported. Although results are not currently available, these guidelines
should prove useful in the future, removing the difficulty of comparing studies which use differing injury definitions and ways of recording and reporting the results.

With respect to this study there are two main problems with the new system. This proposal was only made in 2005, and may take up to a decade for it to be accepted as a standard by all cricket authorities. This means that there will be few results collected using this system and so limited data which can be utilised within this study. Also using the given injury classification, injuries caused to the area covered by cricket pads by ball impacts would be classified as “Other knee injuries” or “Other shin, foot and ankle injuries”. It is indicated that the “mechanism description” should be recorded for each player but whether these will be published is unclear.

This case of impact injuries to the lower limb being poorly reported is a trend repeated in most of the literature. Orchard et al. (2006) provides a paper covering the injury occurrence rates of players in Australia. It relates these to the number of players in each squad and the number of games each squad will be expected to play in a season, also taking into account number of players on the field at one time. It builds up a representative picture of the incidence of injuries for players in each role, but fails to relate the injuries to body position. The injuries that are of interest to this project would fall under either the knee, or the shin/foot/ankle category. There is no reference to how these injuries are caused, whether they are sprains, breaks or impact injuries so this information is of limited use here.

A study by Finch et al. (1999) focuses on the injuries which occur in cricket but also on ways in which these can be prevented. There is considerable interest on the lower back injuries of bowlers, but little covering other cricket injuries in general. Included is a section concentrating on impact injuries, where reference is made to the Hrysomallis study (1996), but does not include any additional information. This study by Hrysomallis is discussed in more detail in section 2.1.2, but concludes that current pads are inadequate around the knee roll to repeated drop tests, extending this to a game suggests repeated balls to the knee roll would compromise its protection and could lead to a knee injury.

A paper by Stretch (2003) follows the injury trends of the provincial and national teams in South Africa. He uses a similar recording system to that proposed in the standard (Stretch et al., 2005a) which gives little information relevant to this study. In the discussion he does mention that the majority of the upper limb
injuries are caused by ball impacts during either batting or fielding, most of these being fractures and joint injuries. In a similar discussion of the lower limb injuries he talks of the majority being muscle strains and makes no reference to ball impact injuries.

There is little discussion of deaths as a result of cricket specifically, but Blonstein (1966) when discussing the medical impact of amateur boxing compares deaths per year across several sports. It is reported that 6 deaths occurred in 1962 in Great Britain and the USA as a result of playing cricket. It should be noted that this was well before the advent of the cricket helmet. There are no papers which reference impact injuries from the ball striking the padded area of the lower leg. Anecdotally, there are cases of lower limb injuries; in particular one case of a knee injury has been reported in a match where the player began to play a stroke and in the process displaced his pad with his bat, leaving his knee exposed, the unprotected knee was then struck by the ball causing a serious debilitating injury. This indicates that if there are no injuries caused by balls striking the pads then the pads themselves are possibly over-engineered for the impacts they are expected to deal with. This provides opportunity for a better engineered product in terms of weight and performance.

All these studies use the amount of playing/training days lost as the indicator of injury severity. It is therefore possible that players do get struck by the ball on the pad and this may cause a contusion of some sort, this may be enough to affect concentration and performance, but will not cause them to have time off and so will not classify as an injury in that context. In this case the level of protection afforded by the pads might be improved upon to minimize these types of injuries and aid player performance, but the justification for this cannot be evidenced.

2.1.2 Laboratory testing

Despite the low incidence of lower leg impact injuries in cricket, the relatively small number of studies testing leg guard performance all suggest improvements that could and should be made to the leg guards. It should be noted that none of these use a representative style of test as proposed in this work.

Hrysomallis (1996) investigated some of the factors that affect the shock absorption characteristics of protective cricket equipment. He used a relatively heavy mass as the impactor with slow impact speed utilising the equivalent kinetic energy principle, which remains a popular rationale behind many test methods.
Nine sets of batting pads were impacted at the ankle, on the shin and on the knee roll three times each. The performance of the knee roll was found to be unacceptable by the author with 6 of the pads failing under the repeated testing at increased temperature and humidity. He concluded that price was not a good indicator of performance and that construction and pad thickness influenced the shock absorption characteristics most.

In his review of batting in men’s cricket, Stretch et al. (2000a) look at both the morphology and physiology of batsmen in cricket, considering the skill of the batting movement and also injury prevention and the role of cricket pads. They cover various areas such as the reaction times required to face a ball and how this process is carried out, the biomechanics of the batting motion and the force applied. In the section on injury there is no mention of impact injuries to the lower limbs but it does provide succinct reviews of the Hrysomallis study (1996), and further work by Stretch et al. on testing of cricket pads (1998). It is stated that some pads are better at absorbing impact forces, giving greater protection, while others reduced the rebound velocity of the ball more. They also hypothesize that these differing characteristics may provide advantages in different types of games, but also noted that pads should be selected for their protection qualities and not their ball rebound characteristics. The need for more testing is emphasized to establish the impact of structure and composition on the pads properties. It is evident that this area of testing requires more attention, which is brought up by Finch et al. (1999) who suggested that further measurement and improvement of the protective performance of padding be done.

There is no further research to the authors’ knowledge of an attempt to create representative testing protocols or any further work in the area of benchmarking protection provided by cricket leg guards. This demonstrates the novelty of this area of research.

2.1.3 Impact forces and loads

Stretch et al (2005b) also compared rebound characteristics of cricket bats, using a setup that could be useful in designing testing procedures for the pads themselves. Three impact speeds were used; 18.6 m/s, 28.1 m/s and 36.4 m/s, these velocities were based on work by Abernethy (1981) describing release speeds of elite fast bowlers and also taking into account a 14.3 % drop-off in speed as described by Penrose et al. (1976). The rig used “gripped” the bat handle in two positions to simulate the players grip as close as possible. Eighteen impacts on each bat were carried out at each speed with a statistical analysis package
used to record the results. The setup is fairly simple and gives a good set of bounding conditions that would be repeatable for pad testing.

In work by McIntosh and Janda (2003) on cricket helmet performance using a range of speeds, 19 m/s, 27 m/s, 36 m/s and 45 m/s, fired a cricket ball from an air cannon at the helmets. In a similar series of test Stretch (2000b) used impacts at 44.5 m/s, this is the highest speed used in any series of tests. Information taken from bowling performances by Glencross and Cibich (1977) found a ball delivered at 40.2 m/s took 439 ms to reach the batsman. Regan (1997) found batters often have just 230 ms to deal with late fluctuations in the flight of a ball approaching at 44.4 m/s. He also discussed spin bowls delivered at 18 m/s would hit the ground 940 ms after release. Others such as Corrigan (1984) found delivery speed of 38.89 m/s or 140 km/h showing that all these values seem to show agreement for the top end speeds. The reproducibility of these was investigated by Portus et al. (2000). The mean ball speed for a group of bowlers over 8 overs was measured at 32.1 m/s.

2.1.4 British Standard critique

Four British Standards exist that relate to the PPE worn in cricket, these are BS 6183-1:2000, BS 6183-2:2000, BS 6183-3:2000 and BS 6183-4:2000. This critique of the British Standard for testing of cricket leg protectors for batsmen (BS 6183-1:2000 and BS 6183-3:2000) will focus on the testing methods used to gather information about their protective qualities. The standard specifies a preparation period prior to testing which acts to “wear in” the pads in an attempt to ensure their behaviour will mimic that of a used set of pads. Hrysomallis (1996) suggested that the temperatures and humidity of this should be changed to simulate hot and humid playing conditions, which can be encountered in certain countries during play, so this is one area where the standard may be improved.

In the test, a steel anvil 350 mm long with a curved surface of 25 mm diameter is used to replace the leg and is rigidly attached to a support frame (figure 2.1). A 50 mm long section in the centre is free from the rest of the anvil and mounted on a force transducer. The pad is mounted on this setup and impacted with a 2.5 kg, 72 mm diameter hemispherical, steel striker which is dropped onto the pad at up to 5.65 ms⁻¹. The maximum allowable transmitted force is 5 kN for the shin region and 6 kN for the knee region. Measured values greater than these, result in the pad failing this test.
The striker in this test is designed to mimic the cricket ball's size and shape. With the mass of a standard cricket ball being approximately 160 g, the speed of impact with a 2.5 kg weight will be nearly ten times less for an equivalent kinetic energy impact. This principle has lead to results which attempt to measure the broader properties of the materials, but in these tests, hysteresis in particular is poorly represented especially for the softer type materials used in the construction of typical cricket pads. This means materials will exhibit different properties depending on the speed of impact with the same force. An extreme example of this is the D3O material that has been used in football shin guards (D3O, 2008), which is viscous at slow loading speeds but the molecules then lock together and become extremely rigid under high strain rates. For this reason, the equivalent kinetic energy principle should not be used in this situation and a lighter mass impactor moving at higher speed would give a much more realistic picture of the pads performance.

The highest impact energy experienced by the pads in a British Standard test is 40 J. The standard states that on the inner shin and inner knee areas, where the highest normal impact velocities are expected to occur in an impact with the pad, should be tested with a 40 J impact. Using the equation for kinetic energy, \( E_k \), by using mass, \( m \), and inbound velocity, \( u \), as given in equation 2.1, it can be shown that a 40 J impact with a 160 g cricket ball would only be travelling at 22.36 m/s. From the information in section 2.1.3, it is clear that this is only half of the bowling speed that could be expected to be faced during a match. It is recommended that should this test continue then a higher energy impact be used, but a lower mass, higher impact speed test such as the one developed in Chapter 5 of this work should be more representative.

\[
E_k = \frac{1}{2}mu^2 \tag{2.1}
\]
Another problem identified with the current testing procedure is the means of collecting the transmitted force data. Figure 2.1 shows the anvil used to approximate the tibia bone along the front of the shin. Impacts to this area will likely be the most painful and damaging due to the absence of soft tissue as protection. However there is only a 50mm long section (2) of this anvil connected to the force transducer (3) to measure the load transferred through the pad. With the current set-up it is possible that the loads be shunted away from the force measurement zone in order to pass this test, this would transfer loading towards the vulnerable knee and ankle joints of a player rather than absorbing force as would be expected.

From inspection of the literature and evidence from play it seems clear that current testing standards are sufficiently robust so as to prevent the majority of injuries, but by implementing some of these changes better optimisation of the pads specific performance may be possible.

## 2.2 Taekwondo

### 2.2.1 Protector design features

The world governing body is the WTF and in the UK the British Taekwondo Control Boards (BTCB), these bodies are responsible for the equipment specification (BTCB, 2008).

The body protector, or hogu, used in taekwondo gives a large scope for re-design. Several limitations have been pointed out in the current design with regards to protection and safety, but also the fit of the garment and the way it fastens. Even small improvements in any of these areas should give a competitive advantage, or a large step forward in design may lead to it being the hogu stipulated for use in major competitions.

The WTF website (WTF, 2009) gives a complete background of the development of taekwondo as an Olympic event. To test the practitioner’s skills and techniques as fully as possible the practice of the martial art had to be full contact. Other martial arts use less protective equipment as they are deemed “semi-contact”, with blows being pulled so as to demonstrate the skill without causing damage, this can be seen as a contrived situation. In WTF taekwondo, the use of full contact, powerful blows necessitates the use of personal protective equipment, even in training, to ensure safety (Zetaruk et al., 2005). Scoring blows in
WTF Taekwondo include punches and kicks to the body and kicks to the head, thus the body protector or hogu and protective head gear are important to an athlete’s safety.

Further to the British Standards (BS EN 13277-1:2000 and BS EN 13277-3:2000) used for testing of the hogus, William Darlington (2006), Chairman of the British Taekwondo control board referee committee and a 5th Dan international referee, has written a letter proposing several amendments and additions to the British and the European standards regarding the protective equipment used in taekwondo. Currently, this includes head gear, hand and foot protectors and of course the hogus themselves. The three main points highlighted by Mr Darlington (2006) are that:

1) As the back is a scoring area (excluding the spine) the standards should specify this as a zone of protection and as such test here also.

2) The shoulder pieces should now incorporate substantial protection, despite this being a non-scoring area. None of the current protectors, have significant protection in this area.

3) The whole area to be protected should be covered by a continuous area of foam with no significant gaps. In particular there should be no gap in the padding between the sides and the back.

2.2.2 Injury rates, types and mechanisms

Although a different style of taekwondo is examined in the paper by Burke et al. (2003), in that no body armour is used and it is light contact, it is still useful. It evaluates the incidence of injuries in taekwondo competitions involving a wide range of participants of varying age, sex and experience level. This paper reports a low injury rate of 0.4/1000 athlete exposures where an injury is reported as a trauma that prevents the combatant from resuming competition on that day. This rate is lower than previous studies reporting between 25/1000 and 127/1000 athlete exposures, but these include high level taekwondo competitions and may not truly reflect the average taekwondo participant. It was found that the head and neck were the most common sites of injury (16/33 recorded traumas) where most occurred as a result of a kick to the face (13/16) even though blows to the face were disallowed under the rules. There was also only one injury reported to the ribs, the area that would have been protected by a hogu, but this low number is most likely
due to the restriction on contact strength. Overall this paper highlights how the injury rate will vary with the level of combatant.

Zetaruk et al. (2005) examined injuries in 5 different martial arts, one of which was taekwondo. They aimed to compare the rate, type and severity of injury in the 5 styles which also include shotokan karate, aikido, kung fu and tai chi. In this study the taekwondo was Olympic style with full-contact sparring, these participants also wore the most protection of all the styles monitored. The greatest number of major injuries were seen in aikido and taekwondo respectively, with 28% and 26% reporting respectively, but also reported the highest number of bruises, a low level injury, with 43% of participants reporting this injury. Injuries in taekwondo were categorised into 5 regions; upper extremities, lower extremities, groin, trunk and the head and neck region. 24.5% of the time a taekwondo injury was reported to be on the trunk, the area protected by the hogu. This was considered a high proportion considering that the hogu was the most substantial piece of protective equipment worn and shows that there is room for improvement on the protection level. Taekwondo had the highest injury rate of the 5 styles, but it is important to remember that taekwondo was the only full contact striking style considered. The emphasis in taekwondo is on fast, powerful kicks which have massive potential for causing injury, 80% of the techniques used in taekwondo are kicks (Serina and Lieu, 1991). It should also be noted that at the moment the padding may afford some protection to the athletes but this tends to have greatest benefit for the athlete executing the kick, not the recipient (Birer, 1996). In this study, injury rates and other information were recorded for competition and training. This also reiterates the importance of the protective equipment for practice as well.

The research by Kazemi and Pieter (2004), is a study of the injury rate at the Canadian National Taekwondo championships. This is particularly relevant to this study as it deals with high level athletes in a competitive arena, which should also give the highest rate of injury. All injuries at the time were recorded on an injury form to document both the injury and treatment received; these data were then used retrospectively to carry out the study. The nature, site, severity and mechanism of injury were all recorded if the athlete was forced to leave the competition, the referee or athlete stopped the competition or in any circumstances where the athlete called for medical attention. The lower extremities were the most commonly injured in the men (32/1000) followed by the face (18.3/1000) and all injuries to the women occurred in the lower extremities (15.2/1000). Receiving a kick was responsible for 27.4/1000 injuries per athlete exposures, with 6.9/1000 of these to the trunk area, the primary zone protected by the hogu. Delivering a kick to the trunk caused
2.3/1000. Of all the kicks, the roundhouse was most often implicated in causing injuries in men, more often the recipient being the injured party. The overall injury rate was higher than that given by Zetaruk et al. (2005) but this is due to all samples being taken from competition where risk of injury is higher than training, also the skill of the participants was greater leading to more powerful attacks with no change to the protective garments. Other studies have recorded higher injury rates with Zemper and Pieter (1989) finding 127.4/1000 exposures in American elite male taekwondo athletes and Pieter et al. (1995) finding an injury rate of 139.5/1000 for European men, but these differences may be explained by recent rule changes and a more stringent application of these rules as hypothesized by the author.

2.2.3 Laboratory testing

The only work to the authors’ knowledge on laboratory performance testing of taekwondo hogus was carried out in-house as part of a final year project at Loughborough University. The unpublished work by student, Craig Burgess, performed a series of tests on taekwondo chest guards after designing a rig to create a representative test. He used a simple drop test rig to impact the protectors and produced results for four hogus from four leading manufacturers. Each of the hogus displayed different rebound characteristics across the series of tests despite all being manufactured to pass the same testing standard. All guards reduced the force transmitted to the force plate, though some proved to be more effective at reducing force than others. No significant conclusions were drawn by the author but the methodology of the tests is useful.

There is no further research to the authors’ knowledge of an attempt to create representative testing protocols or any further work in the area of benchmarking protection provided by hogus. This demonstrates the novelty of this area of research.

2.2.4 Impact forces and loads

In taekwondo the majority of attacks are kicks, although punches are allowed to the body, the power generated by a kick would be significantly higher and as such this should be the benchmark for testing the equipment. The maximum protection is required from the more powerful attacks, so knowledge of forces transmitted in competition by kicks to the torso is necessary to set boundary conditions. The problem with most experiments of this sort is that force measurement devices that can be used in competition are limited and no work has been done on kicking in taekwondo using this equipment. It is also likely that force readings
taken in a laboratory setting will tend to be higher than those in a match, as athletes can fully commit to the strike without fear of retaliation.

One of the few studies done where force measurements are taken outside of the laboratory situation is that of Pierce et al. (2006). This experiment used the “best shot” system, which uses lightweight flexible sensors to record punch force on contact. This was then used to measure punching force during a series of six boxing matches. The problem with previous studies is that when punching a stationary target in a laboratory, it is a lot easier to impart the maximum force possible. There is no fear of being open to a counter attack or having to throw another punch afterwards. This could make the forces recorded in these types of studies much higher than what would be experienced in the ring. In the ring, the maximum punch force was recorded by a cruiserweight fighter, he achieved a peak force reading of 5358 N whilst punching, whereas the winning heavy weight fighter only registered a peak force value of 3554 N. It was found that there was no significant trend between mass of the fighters and maximal punching force. The mean punch force taken across all impacts for three rounds for the hardest hitting heavyweight was 23.2% of the mean punch force measured in previous “in lab” experiments, although the maximal force of the best cruiserweight punch does come a lot closer to these values. These values are all considerably higher than the 150 N average force measured by Walker (1975) for a karate punch. Blum (1977) reported that the maximum speed of a punching blow is between 7 m/s and 14 m/s depending on the thrower and that the mass of the hand and arm combined is about 7 kg. Using this information a comprehensive representation could be used as a basis for a punching rig to be used to test equipment.

Pedzich et al. (2006) set bounding conditions for modelling impacts when comparing the dynamics of various leg strokes in WTF taekwondo. For 5 high level athletes of different weight classes, measurements of the peak stroke force, time to peak stroke force, and average value of the stroke force were taken during performance of two different kicks. These being the side-kick (yop-chagi) and spinning back kick (dwit-chagi). Using force plates the values were recorded for each leg. Of most interest is the peak force values which were given as follows:

<table>
<thead>
<tr>
<th>Kick</th>
<th>Side</th>
<th>Peak Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yop-chagi</td>
<td>Right</td>
<td>( F_{\text{max}} = 9015 \pm 2392 \text{ N} )</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>( F_{\text{max}} = 8294 \pm 2308 \text{ N} )</td>
</tr>
</tbody>
</table>
Dwit-chagi  
Right  -  \( F_{\text{max}} = 8569 \pm 2381 \) N  
Left  -  \( F_{\text{max}} = 7751 \pm 2570 \) N

In general, it was also observed that there was a significant connection between the body mass and the peak stroke force. Although a significantly stronger kick was registered by one of the lighter athletes, it was observed that he had the highest skill level of all those tested. The force values display a large level of variability as they cover the range of multiple maximum efforts for 5 different sized athletes of differing skill levels. These values give a baseline for testing which would be higher than those experienced in competition due to the contrived nature of the setup. The athletes had no worry of counters or having to avoid other attacks so could commit fully to the kick and register a contact force much higher than possible in an actual match.

Using these peak force values for the two types of kicks and relating them to the small drops in measured peak force between the lab and in the ring for the boxing study an initial estimate for the forces that the hogu will be exposed to during a fight can be made. If it is assumed there is a similar drop in percentage of the peak force value for the kick compared to a punch between lab and competition conditions, putting this down to the athlete not having as much time to set themselves for the attack and always having to be prepared for a counter, then the encountered peak force could be anywhere from 1800 N up to 7000 N. This is a considerable range so further investigation will be required before settling on a final value.

### 2.2.5 British Standard critique for Taekwondo

In this critique of the British Standard for testing of trunk protectors for martial arts, the focus will again be on the testing methods for the items of protective equipment. Although there are six parts to the British Standard, BS EN 13277-1:2000, BS EN 13277-2:2000, BS EN 13277-3:2000, BS EN 13277-4:2000, BS EN 13277-5:2000 and BS EN 13277-6:2003, only part 1 and 3 will be considered here as they relate directly to the hogu and its testing as opposed to the other protective garments used.

For the impact testing in this standard, a 2.5 kg weight is used. In this case, opposite to the cricket, this mass is too small to represent the inertia forces that would be present when struck by a 20 kg leg (Peebles & Norris, 1998). The impact energy of 12 J would coincide with an impact velocity of 3.1 m/s and is considerably slower than either a hand or foot would be expected to be moving at impact. Overall this results
in an impact with less energy, force and momentum than would be expected of a kick given by a skilled practitioner.

Another variable that distinguishes taekwondo from the other sport being studied is that its competitors are separated during competition into weight classes and only fight opponents of similar physical attributes. Through this identification of small competitors not having the same physical abilities as larger ones it would seem likely that the protective garments supplied should mirror this. In its current form, the standard is able to accommodate different sized trunk protectors, but there is no increase in loading to mimic the change in impact force which would accompany a change in level of competition or weight class. Another issue is the size of impactor, to follow the change in fist size which would accompany smaller or larger competitors. It is possible for a smaller fist to produce less force but impact with a greater pressure and still lead to injury.

2.3 Other Sports

Perhaps due to the greater availability of money in the sport, linked to its greater global popularity, a large amount of research has been carried out on the PPE in football, namely the football shin guard. The greater amount of research carried out in this sport can indicate the direction that further research in both cricket and taekwondo will take and it is even possible that some of the outcomes may be mirrored.

Performance of football shin guards for direct stud impacts by Ankrah and Mills (2003) provides useful data on the background to the game of football. It discusses testing standards for football shin guards, leg injuries, previous testing in this area and also a brief explanation of how they decided on their particular rig for testing. Lees and Nolan (1998) give a review of the biomechanics of soccer which gives particular emphasis to the biomechanics of kicking, giving various values which are used in other studies to justify the boundary conditions for testing. Figure 2.2 below, taken from Isokawa and Lees (1988) shows the speed of the various sections of the leg throughout the kicking action, with the toes and ankle going over 15 m/s and 12 m/s respectively at ball impact. Estimates to contact force with the ball suggest that peak force may be as high as 2200 N. The effectiveness of shin pads in reducing the severity of impact has been evaluated by Lees and Cooper (1995), they attempted to measure shin guard performance using a 5 kg mass dropped from 400 mm on pads mounted on a wooden anvil. In this test the pads reduced the impact deceleration by 40% – 60%. Also suggested is that although effective at these energy levels, there is not sufficient material in the
pads to be effective at much higher energy levels. Testing at these higher and more representative of game
energy levels should be paramount in the study of football shin guards.

Figure 2.2 – Graph of the velocities exhibited at each segment of the leg during a soccer style kick (Isokawa
and Lees, 1988)

Using velocities from the study above, along with estimations of mass of the foot, Ankrah and Mills (2002)
suggests that the kinetic energy for testing would need to be around 10 J. In experiments at these levels
Phillipens and Wismans (1989) used a kinetic energy of 5.3 J and found that guards reduced the peak force
by 28% - 53%. Whereas for impacts of between 8 J and 21 J, this force absorption reduced further with
Francisco et al. (2000) finding reductions of only 11% - 17%. van Laack (1985) performed a series of tests
on shin guards and found that they decrease the magnitude of the peak force by increasing contact time, this
effect was optimal when forces were less than 3000 N.

In two papers on testing of football shin guards and testing of ankle protection, Ankrah and Mills (2002,
2003) used a 10 J impact and the equivalent kinetic energy principle to justify the use of a heavier impactor
at a slower impact speed. In the ankle protection tests, the foams used are claimed not to be rate dependent,
but this runs contrary to in-house experience. The 10 J value comes from the 16 m/s toe speed given earlier
by Isokawa and Lees (1988) and an effective mass of the articulated bones of 0.1 kg, this gives an effective
kinetic energy of 13 J. This derivation of a representative impact condition is backed by an understanding of
the mechanism and a sound understanding of the mechanics involved. Knowing where the derivation for the
tested energy levels has come from gives more weight to this experimental practice over the unexplained
values of the British and National Operating Committee on Standards for Athletic Equipment (NOCSAE) standard (BS EN 13061:2001 and ND 090-06m07). The NOCSAE standard uses only a spherical indentor impact test, whereas the BS EN 13061:2001 is more thorough and includes stud impacts and a laceration test.

For blunt impact testing NOCSAE use a 5 kg mass impacting at a velocity of 1.73 m/s, and the BS EN 13061:2001 uses a 1 kg mass impacting at 2 m/s. The variation in energy between these two tests is significant at 7.5 J for NOCSAE and 2 J for BS. These are both lower than the 10 J suggested by Ankrah and Mills (2002), and the NOCSAE standard achieves this with a heavy mass and slower impact velocity than would be recommended for the test to be truly representative.

The stud impact test in the BS suggests a more realistic 15 J impact energy, with a 1 kg mass impacting the pad through a stud at 5.4 m/s. The allowable mean transmitted force for this test is 2 kN. The laceration test included in the BS covers another aspect of protection and tests the pads ability to withstand damage from a stud dropped along the pads length. Large open wounds could result if pads were to fail in this situation in a game so this is a useful addition.

2.4 Conclusions

From an extensive review of the literature several points are drawn for each of the two focus sports that distinguish the two garments and identifies independent objectives for each of the sports. In cricket the low incidence of reported lower limb injuries indicates that the protection provided is adequate, though the limited laboratory testing does not support this. The information required to setup a representative test has been documented, and despite its adequate protection level indicated by low injury rate the British standard testing for this garment was critiqued.

In taekwondo the current injury level of participants in the area protected by the hogu is analysed, the incidence rate is high but no life threatening injuries are reported. Whether the protection level needs increasing or not is unclear, as some injury seems to be part of the full contact nature of the sport. Laboratory testing of the garment was inconclusive, but between a critique of the British standard and recommendations by William Darlington, it is clear that alterations to the testing specifications are required.
Brief analysis of research on football shin guards shows that the testing used in the research uses significantly different conditions than that in the British and NOCSAE standard. The research based testing relates their boundary conditions to the game itself and recommend an update to the testing protocols applied in the standards themselves.

Absence of any literature covering true attempts to create representative testing methodologies for these items of PPE shows the novel nature of the work presented within this thesis.
3. Development of a High Speed Impact Test Procedure for Cricket

Having discussed the current testing standards used for establishing minimum performance levels, and recommended the development of testing procedures that re-create the conditions of impact experienced in a game more closely, the aim of this chapter is to report on the initiation of this process. The work in this chapter proposes a new approach to product testing, based on matching the energy and momentum of the impactor. A standard force transducer based setup was used to measure the force values. High speed video recordings were analysed to measure other variables, such as the degree of deformation, the contact time and the coefficient of restitution of the impact in order to analyse pad performance further. The merits and drawbacks of this approach are discussed and possible improvements are suggested.

3.1 Background

The British Standards for testing of cricket leg guards (BS 6183-1:2000 and BS 6183-3:2000) provide a standardised means for defining the adequate protection levels of cricket leg guards sold to players. These tests allow a similar impact to be recreated using a slower moving object of increased mass, based on matching the kinetic energy of the original impact. This is generally known as an ‘equivalent kinetic energy’ impact. This is particularly useful when simulating a high velocity, low mass impact such as that of a cricket ball as these exact conditions may be difficult to replicate under controlled lab conditions.

The effective impact energy of a collision between two bodies is defined as the energy input until the time where both bodies have a common velocity (Ankrah & Mills, 2003). In this scenario the first body is the ball, \( m_1 \), and the second is the pad attached to the leg, \( m_2 \), and \( u_1 \) is the incoming velocity of the ball. Assuming the leg of the player is rigidly planted on the floor its effective mass can become infinite, so post impact velocity remains at zero. The effective kinetic energy of this impact becomes equal to that of the approaching ball:

\[
E_e = \left( \frac{m_2}{m_1 + m_2} \right) \frac{m_1 u_1^2}{2} = \left( \frac{\infty}{m_1 + \infty} \right) \frac{m_1 u_1^2}{2} = \frac{1}{2} m_1 u_1^2
\]  

(3.1)
In practice, the energy available to cause injury is likely to be lower as some of the energy can be dissipated through the soft tissues of the leg. It is also possible for the leg to be struck whilst not planted on the floor; the effective mass of the leg would then need to be accounted for lowering the effective kinetic energy of the impact.

The other important consideration in testing of PPE is strain rate. This is an issue of lesser importance for more rigid materials, as demonstrated in the testing of motorcycle helmets Gilchrist and Mills (1996), but can have a large effect on the polymer foams in particular. Davies and Mills (1999) demonstrated this effect on viscoelastic polymer foams showing a large change in performance between loading rates of 1 m/s and 10 m/s.

Strain rate, is the change in strain, $\delta \varepsilon$, over the change in time, $\delta t$, and can be calculated as follows:

$$\dot{\varepsilon} = \frac{\delta \varepsilon}{\delta t}$$

(3.2)

For a small, finite period of time, this can be approximated to:

$$\dot{\varepsilon} \approx \frac{d \varepsilon}{dt}$$

(3.3)

Due to the softer materials and polymer foams used in cricket leg guards it is highly likely that their performance under impact will be strain rate dependent, similar to the foams of Davies and Mills (1999). Showing different levels of protection depending on the rate of deformation, the rate of deformation being related to the impact speed of the impact. The equivalent kinetic energy test used in the BS testing protocols keeps the energy constant but decreases the impact velocity, which will therefore change the strain rate of the impact. This difference in strain rate from the impacts encountered in a game mean that cricket leg guards may exhibit different properties during testing which could compromise player safety.

In order to create a test representative of the conditions in a match, the kinetic energy of the impact should be kept the same, but the impact speed should also be kept the same, which should then lead to an appropriate strain rate in the tested item of PPE. If impact velocity needs to be kept consistent then so does the mass of the impactor in order to match the kinetic energy of the impact. Therefore as a first
approximation the mass and velocity of the impacting object should be matched to that of an in-game impact to approach a representative test.

3.2 Approaching a Representative Test

Previous literature and information gathered and reported in Chapter 2 has revealed the need for a test of improved realism to be developed. Within the following section discussion begins on how a new representative test was implemented. The aim was to recreate conditions experienced on the playing field as closely as possible using currently available equipment. Similar testing using high speed ball impacts and force measurements have been performed previously in-house, so several pieces of important equipment were already available which saved significant time. Instead of having to design and develop a test and the equipment from scratch a representative test could be approached using readily available equipment.

3.2.1 Impactor

For the impactor to be representative of game impact speeds, from the literature it can be seen that the highest achievable bowling speeds are likely to be around 40 m/s at release (Stretch et al., 2000a, Glencross & Cibich, 1977, Corrigan, 1984). This is the measured speed of the delivery just after the ball has been released, therefore, to allow for the possibility of full-toss deliveries (where ball speed would not be lost on bouncing) and the athletic improvement of players leading to higher bowling speeds. Four speeds were specified to cover the likely in-game range; 13.42 m/s, 22.36 m/s, 31.31 m/s and 40.25 m/s (30 mph, 50 mph, 70 mph and 90 mph). This would also allow trends in the pad performance with speed to be observed.

These ball speeds were achieved using an in-house manufactured pneumatic ball cannon, designed previously for the purpose of replicating high speed ball impact. The ball cannon uses pressurized air, applied to propel a given projectile along the 1.3 m barrel. The air pressure can be altered to achieve the required impact velocity. Different barrels are used for different balls to give a close fit to the ball and a consistent firing velocity, the barrel also increases the accuracy of the impact location. By having this piece of equipment available, significant design work was saved in developing a device to launch the ball at game specific velocities.
To carry out the actual impacts a hockey ball was used, since it is of a similar size and mass as the cricket ball but has two major advantages. Firstly a hockey ball has a smooth external surface so no matter which side impacts the pad, a consistent pressure will be applied for each impact. Cricket balls have an external seam running around their circumference; this may cause uneven pressure distributions through impact, the ball to rebound differently to expected and may also cause inaccuracy, as the ball may not fit in the barrel of the cannon so well. Secondly, cricket balls have a tendency to wear and degrade with repeated impacts more than hockey balls, this is why they are changed regularly during match play, and this degradation affects the balls performance and thus its rebound characteristics altering results. For both these reasons, using a cricket ball for the impacts would introduce greater variability to the results.

![Figure 3.1 – Graph comparing compressive stiffness of a cricket and hockey ball](image)

Figure 3.1 above shows compressive load against compressive extension for a cricket ball and a hockey ball carried out on an Instron compression testing machine loading at 60 mm/min. Four repeats were carried out to find the stiffness of a hockey ball and a cricket ball, tested both on its smooth face and on the seam. The results show that the seam and smooth faces have differing compressive stiffness', which would reduce the reliability of impact test results carried out with a cricket ball. This graph also shows that the hockey ball is a quarter the stiffness of a cricket ball for repeated loads at these compression distances. Previous testing
carried out in-house, where intact cricket leg guards were subjected to quasi-static compression testing using the same Instron machine loading at the same loading rate found stiffness values 10 times lower than those found in either of the balls. The use of a solid steel cylindrical leg anvil and hockey ball give effectively rigid impact surfaces so that the reactions of the pad itself are the main contributors to measured performance during the dynamic testing.

3.2.2 Force Transducers

The force data was recorded using a Kistler model 9067 quartz piezoelectric force cell. A force transducer may be defined as a sensor that can convert a forced input into a measurable output signal. Depending on the type of transducer, this output may take a variety of forms but most commonly an electrical signal output is achieved. The electrical signal can be the result of a change of resistance such as in a strain gauge type force transducer, or the signal can be generated directly by the force such as in a piezoelectric crystal transducer that is widely used for dynamic force measurements. Most commonly, the piezoelectric material used in these sensors is a form of quartz that has a high stiffness; this gives it a high natural frequency and makes these transducers suitable for dynamic tests.

There are two main issues with force transducer usage, firstly it is important that the transducer is mounted rigidly since if the mounting surface moves during the applied force, this movement is sensed and vibrations are introduced into the force signal. Secondly, it is important that the natural frequency of the system remains significantly higher than the frequency of the impact. As the impact frequency and system frequency approach one another, vibrations will be introduced into the force signal making it less reliable.

\[
\omega_n = \sqrt{\frac{k}{m}} \quad \quad (3.4)
\]

\[
f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad \quad (3.5)
\]

The natural frequency of a system is dependent on the mass and stiffness and can be calculated using equations (3.4) and (3.5) (Brach, 1991), where m is the mass mounted on the transducer, k is the stiffness of the transducer and f and \( \omega_n \) are the natural frequencies in radians and hertz respectively.
As the mass increases, the natural frequency decreases. The effect that vibration can have on a signal can be seen in figure 3.2, these data were generated for illustrative purposes. Figures 3.2) and 3.2b) show two measured signals individually, but figures 3.2c) and 3.2d) show the effects of these being measured together. The only difference is that the smaller ‘noise’ signal is half a period out of phase in figure 3.2c). This leads to a significant difference in the measured signals, specifically if only peak values were given. Hence elimination of system vibration can be a significant factor in the accuracy obtained.

![Figure 3.2 - Graphs of amplitude plotted against time displaying the effects of high frequency sine wave noise on a lower frequency higher amplitude sine wave](image)

Force transducers have a wide variety of applications, and if used correctly have potential to give an accurate reading of the force applied. Within this testing, a leg shaped anvil is attached to the front of the transducer to mimic the size and curvature of a human leg, and the force cell is mounted between two steel plates. If we consider the total mass of the anvil and front face together, m, the mass attached to the front of the force cell is 11.09 kg. The cell has a stiffness, k, of $4.5 \times 10^9$ N/m, so using equation (3.4) and (3.5) below we can find the natural frequency of this setup as 3.167 kHz.

Mills (2007) suggests in material impact tests keeping the resonant frequency of the system above 10 kHz. This would involve reducing the anvil and front face mass to below 1.14 kg. The system’s low natural
frequency is not a desirable condition as there is a higher likelihood of the natural frequencies of the system being excited by the impact that would cause more noise in the force readings.

### 3.2.3 Measurables

In addition to force, three other variables were monitored throughout the experiment; these were Coefficient of Restitution (COR), contact time and deformation.

The COR is defined as the ratio of the inbound to outbound velocities of the impacting objects and takes the form of a value between one and zero, and is related to the amount of kinetic energy dissipated during an impact. An entirely elastic collision where no energy is lost will have a COR of one, if two objects strike each other and lose all kinetic energy so remain together at the position of impact then the COR is zero. The equation for two objects of inbound velocity \( u \) and outbound velocities \( v \), is:

\[
COR = \frac{v_1 + v_2}{u_1 + u_2}
\]  

(3.6)

Which for a fixed rigid anvil impact, where only one object is moving such as the one suggested here can be simplified to a ratio between the inbound and outbound velocities of the impactor:

\[
COR = \frac{v_1}{u_1}
\]  

(3.7)

This value will be used to show how much energy the pad is absorbing throughout the impact assuming that the energy loss in the impactor and anvil are negligible. Although not a key indicator of pad performance in terms of injury it has been suggested by Stretch et al. (1998) that a higher COR value may be desirable during test matches and a low COR during a tightly fielded one day match. In test matches, the fielding team will generally be more spread out so a high COR pad could be used just to deflect the ball away far enough to generate extra runs. In one day matches, with closer fielders a high COR may allow the ball to rebound off the bat, then the pad and then be caught to dismiss the player, a low COR in the situation would kill the balls
rebound and prevent this. This variable will also give insight into the mechanisms by which the pads themselves will be providing protection.

Another monitored variable is the contact time of the impact. This is measured visually from high speed video data of the impact by recording the time of the frame of first contact between pad and ball, to the frame where they are no longer in contact. A longer contact time gives the leg guard a longer time to slow the ball down and reduce its velocity; this means a lower deceleration and thus a lower measured force value. The deformation of the leg guard is also measured in a similar way, the pixel position within the image of first contact between ball and pad and the point of maximum deformation is measured from the high speed video and converted into an equivalent distance to give this. This value indicates whether the pad has reached its maximum compression (known as “bottoming out”) and has consequently reached its limits of providing protection.

Monitoring of all these variables should give a clear picture of the leg guards’ performance and how this is achieved by supplementing the force data.

3.3 Experimental Setup

A simple schematic of the setup used is illustrated in figure 3.3, this shows the main equipment used. The pad is attached to a leg anvil and balls fired at appropriate velocities to designated locations. Force data is recorded using a Kistler model 9067 quartz piezoelectric force transducer, attached to a Lecroy 4 Channel 9304C oscilloscope. Other impact data was derived through video analysis of the high speed video captured at 8000 fps by the Photron Fastcam Ultima APX video camera, further details of the analysis method used are given in section 3.6.1.
The ball is fired from an in-house designed pneumatic air cannon (section 3.2.1). The barrel size is such that a hockey ball can just fit inside. The cannon uses pressurized air to project the ball down the barrel and at the target; the speed of propulsion is varied by adjusting the air pressure of the pneumatic system, a higher pressure giving a higher ball velocity.

The light gates were setup to automatically trigger the high speed camera recording. The high speed camera was setup above the mounted pad looking straight down its length, figure 3.4. The video output from the
camera was analysed to give details of the balls inbound and outbound velocities, contact time with the pad, the amount of deformation of the pad and the rebound angle of the ball. A series of spotlights were used to light the impact zone as much as possible to improve visibility of the image on the captured video.

The force transducer is used to obtain data on the peak force of the impact. It is important that the force transducer is attached to a rigid structure so as to minimise the lack of clarity caused by external vibrations on the force output. The cage it is attached to provides protection to the operator as it stops balls rebounding and damaging people and other equipment in the lab.

The output voltage from the force transducer is displayed on an oscilloscope, which plots the force experienced against time. The oscilloscope outputs all data to an ascii file which can be saved directly to a USB memory stick by using the built in interface, this data was then analysed in Excel. This saves complications of having to operate another computer to deal with the force data. The oscilloscope is set to start recording data a set time before the ball impacts. For all impacts the time base was set at 100ms, this provided ample detail for the collected data whilst giving a long enough signal to witness the damping however the voltage needed to be altered for each impact speed for optimal resolution.

Figure 3.5 – The pad attached to the anvil
On the front face of the force transducer is mounted a cylindrical steel anvil, this cylinder gives a rigid impact surface and its curvature means the mounted pad forms in a similar way to being on a players leg. To attach the cricket pad to the leg anvil two external elasticsed straps were used, as shown in figure 3.5. Using the pads own straps may have given a better idea of how the pad would react under actual use, but because of the size of the anvil and the various positions required to test, the pads strapping would have been inadequate to hold the pad firmly on the leg form. Using external straps allowed the pad to be held above and below the impact site, allowing just the reaction of the pad to be tested.

![Figure 3.6](image)

*Figure 3.6 - The points to be impacted and the zones of protection as defined by the British Standard*

In the British Standard, BS 6183-3:2000, four areas of protection are identified, with each of these areas having a different specification in terms of the level of protection. The highest level of protection is required on the inner shin area, figure 3.6, based around the position of the exposed tibia bone. With minimal soft tissue protecting the front and inner side of this bone, adequate protection is necessary from the leg guard. For this testing, it was decided to take twelve sites around this designated inner shin area to investigate the variation of impact characteristics in this area, figure 3.7. Each site was impacted five times at each speed to ensure reliability of the results.
3.4 Preliminary testing

A preliminary test was carried out by firing the hockey ball at the unprotected anvil. This gave an indication of the repeatability of the ball speeds from the canon and the variance in the peak force measured values. The air pressure of the cannon was adjusted to achieve the required ball speed before measuring the force values. The correlating pressures and ball speeds were: $2.0 \times 10^6 \text{ kg/m}^2$ for 13.42 m/s, $2.7 \times 10^6 \text{ kg/m}^2$ for 22.36 m/s, $4.3 \times 10^6 \text{ kg/m}^2$ for 31.31 m/s and $6.1 \times 10^6 \text{ kg/m}^2$ for 40.25 m/s. These values were also used in the pad testing.

Figure 3.7 – The Cricket pad marked for testing
In figure 3.8 the relationship between the inbound velocity of the hockey ball and the peak force induced in the force transducer has been plotted and a linear “line of best fit” drawn. The range measured for each specified speed was found to be low, between 1.1 m/s and 1.63 m/s across all target values. These small fluctuations in the velocity of the ball represent a variation of only 3.2% however the variation in measured force was as high as 13% for 40.25 m/s (90mph) impacts. This variation in force may prove a source of error within testing.

The small amount of variation within the speeds was attributed to small fluctuations in the air pressure to the cannon or an incomplete seal of the ball in the canon varying between impacts. The force range variations were likely to be caused by inaccuracies within the ball cannon. Small inaccuracies leading to impacts that were away from the centre-line of the anvil, are likely to have reduced the peak force transmitted and introduced inaccuracies into the results. The inaccuracies in force measurement of off-centre impacts will likely be reduced with the introduction of PPE to the test. The equipment will spread the contact area of area and reduce the significant drop in force associated with an off-centre impact. Force variations whilst testing PPE would be expected to be lower than that measured here.
3.5 Methodology

- The test area was marked out on the selected cricket leg guard and each individual impact position was also indicated.
- The leg form anvil was attached to the force transducer and cage.
- The high speed video camera was then mounted above the cage looking directly down onto the leg form.
- The high speed video was set to record at 8000 fps.
- The triggering system using the light gates to commence recording was then set up.
- The pressure of the air cannon was set.
- The cricket leg guard was then strapped to the leg form, ensuring that the ball cannon was aligned with the first impact position.
- For each impact that was carried out, the force trace data and high speed video were recorded.
- The cricket leg guard was re-aligned and a second impact carried out.
- This was repeated until 5 impacts were completed on the first site.
- This same procedure was then repeated across all 12 impact sites with 5 impacts at each.
- This was repeated for the 4 impact speeds.

3.6 Dealing with High Speed Video Footage

3.6.1 Method

Apart from the primary variable of force measurement, all other data for this experiment is taken from the high speed video. To extract the information from the recording a suitable video analysis tool was required. Image Pro Analyser 6.2 was used. This software package allows the user to move through the video frame by frame, marking pixel positions. These positions can be used along with known length dimensions from the video to convert a measured number of pixels into a displacement, marking these on-screen. It also gives control over brightness, contrast and gamma features to manipulate the clarity of an image, figure 3.9.
Analysis of the recorded video allowed extraction of the inbound velocity, the outbound velocity, the contact time, the deformation of the pad, the rebound angle of the ball and the distance from the intended impact site to the actual contact. To this end, a step-by-step process was developed to extract the information as succinctly as possible. To mark the balls position each time, the best-fit circle feature was used, this required three points on the circles perimeter to create a circle around the balls position.

To fully analyse a video, it was first loaded into Image Pro Analyser 6.2 and the brightness contrast and gamma were adjusted to obtain the clearest picture possible. The frame number was advanced until the whole ball was on screen, its position was marked using the software and the frame number noted manually. Again the frame numbers were advanced until the ball was seen to first contact the leg guard, and again the position and frame number were taken. Position and frame number were also recorded for the point of maximum deformation of the cricket leg guard, the point where the ball lost contact with the guard and just as the ball was about to leave the screen again. The position of the leg anvil was taken to define a set origin position throughout. Once complete, this generated a complex series of annotations on screen, an example of which is shown in figure 3.10. These data were then exported to Excel and, using the diameter of the ball as a reference length, together with the frame rate, the displacements and times could then be calculated from the pixel lengths and frame numbers. This then allowed the desired variables to be calculated.
3.6.2 Variability

In order to define the variability of measurements taken from high speed video footage using Image Pro Analyser three videos of ball impacts on padding were selected, these were then fully analysed three times each on three separate occasions, at least 24 hours apart, to replicate the possible variation introduced by large volumes of manual video processing carried out over several days. The values taken from these nine repeats for each video were then averaged to show the inherent variability of these measurements.

The three videos selected were chosen to represent different impacts. Video 1 was a hockey ball striking leg guard 3 whilst being worn by a player taken from work carried out in section 5.3, Video 2 a 2.75 kg shot dropped from 1 m onto a piece of blue Confor foam which is discussed in section 9.2.3, and Video 3 a high speed ball impact against cricket leg guard 2 which is covered in detail in Chapter 6. The exact details of each experiment are unimportant, but these three sample videos represent different impact conditions to give an indication of the human error in the video analysis process.

All the data was then compiled from each of the nine separate analyses. A mean value was taken for velocity, COR contact time and deformation for each of the three experiments. This mean was then compared to the highest and lowest measured value for that experiment to find the variability as a percentage. The results of this are plotted below.

Figure 3.10 - A screen grab from the data analysis software after all the important ball positions and lengths have been marked

Figure 3.10 - A screen grab from the data analysis software after all the important ball positions and lengths have been marked
The results of this investigation are shown in Figure 3.11. Across all videos it can be seen that the velocity measurement is the least variable with most values varying by less than 1%. The contact time results have the largest variability of up to 7% in the case of Video 2. The deformation values are also variable by up to 5% either way, no deformation was measured in Video 2. Overall, all values show less than 7% variation from the mean. This value represents the experimental error that can be attributed directly to the human error in measuring values from high speed video data and is included in results as a part of the uncertainty of the experimental procedure.
3.7 Results

The testing methodology laid out in Section 3.5 was carried out. The transmitted force values noted and the video analysis methods laid out in Section 3.6 were carried out to find the deformation, contact time and COR. The results of these are presented in the following sections. The purpose of this experimental procedure was to evaluate the efficacy of the testing methodology. The selection of the specific cricket pad was inconsequential; the desired outcomes were the various positive and negative outcomes of the testing procedure.

Throughout the testing, the impact velocity was increased from 13.42 m/s (30 mph) to 22.36 m/s (50 mph) and then to 31.31 m/s (70 mph), where the experiment was halted due to permanent damage to the pad. At cessation, a total of 5 impacts had been carried out at each of the three impact speeds, a total of 15 impacts at this point on the pad. One of the canes in the pad had been broken by the repeated impacts and stitching on both the inside and outside had started to become undone. The cotton material on the inner of the knee roll had also torn. Figure 3.12 shows the damaged stitching and deformation to the cane structure of the pad.

![Figure 3.12 - Damaged stitching and permanent deformation in the pad](image)

In the following sections 3.6.1, 3.6.2, 3.6.3 and 3.6.4, the colour plot graphics displayed uses the mean value of the 5 impacts at each impact point, the 12 points of the inner shin region were then plotted for the indicated ball velocity, the space in between these points represent a linear interpolation to give a method of
clearly displaying the trends. The colour plots across the three speeds are presented using the same scale to allow comparison of reaction across the 3 ball velocities.

### 3.7.1 Coefficient of Restitution

![Figure 3.13 – Colour plots showing distribution of COR response across the leg guard](image)

Figure 3.13 shows the distribution of COR around the pad when impacted at the three ball velocities. Considering the slowest impact (13.42 m/s) first, this visualization shows a clear pattern with regards the change in COR with position, which can also be related to the pad’s construction. The value of COR was found to vary from approximately 0.27 in the central top region to nearly 0.4 near the bottom, for a notional impact speed of 13.42 m/s. This variation lies within an area defined by the same testing regimen within the British Standard.

A similar trend was seen at 22.36 m/s, where by the central region exhibited a lower COR than the sides for the same vertical position, with a general trend of high COR to low, travelling vertically up the pad from the lower shin region. Once the impact speeds reach 31.31 m/s, a similar pattern can still be seen. Overall the pattern of COR distribution is similar across the three speeds, with only marginally lower COR values.
indicated at the highest impact velocity. It can be hypothesized that as the thickness of protective material increases up the central region of the pad a greater amount of material is able to dissipate a greater amount of energy leaving the ball with less kinetic energy post-impact and thus a lower rebound speed and COR, though further work would be required to confirm this.

3.7.2 Contact time

![Figure 3.14 - Colour plots showing distribution of contact time response across the leg guard](image)

Figure 3.14 shows a visualization of the contact times of the impacts in each position at each ball speed. The trend shows lower contact times at the bottom of the pad increasing as the impact position moves up for each impact velocity. Similar to COR, this can be related to the amount of protective material available. The ankle zone has the thinnest padded layer, and the contact times are the lowest, the thickness of protective material visibly increases up the pad and in accordance the measured contact times also increase. The knee roll is the thickest area of the pad and accordingly, at all impact speeds has the highest contact time. This trend is least visible at the highest impact velocity.
It can also be seen that the contact times decrease as the impact velocity increases, and that the range of displayed contact times also decreases. The smaller range of measured contact times at higher impact speeds is likely due to the materials in the pad reaching full compression and “bottoming out”, if this occurs the impactor will be moving in and out of the impact at higher velocities and register a lower contact time.

### 3.7.3 Peak force

![Colour plots showing distribution of transmitted peak force response across the leg guard](image)

The variation of peak force with position and speed is shown in figure 3.15. Across all three impact velocities, lower peak forces are measured at the top of the pad where padding is thickest and higher peak force values towards the bottom where padding is thinnest. The variation by position of peak force inversely mirrors that of the contact time, with high peak forces coinciding with low contact times, suggesting that these two variables are inextricably linked. Peak force at a particular ball velocity was greatest where the least padding is present on the pad near the ankle and reduced up the pad to where the most padding is apparent.
One source of error worthy of discussion is the identification of the peak force values. Within each force trace the highest value achieved at the point of impact was taken as the peak force value for that particular impact. The traces from which this number was extracted had excessive vibrations (figure 3.16), and whether the peak values could be fully attributed just to the impact itself or whether it was caused by vibrations within the system was unclear, although these results were clearly repeatable, this lead to uncertainty in the results. In order to improve this testing methodology, a more advanced filtering method could be used to reduce the influence of vibration or the system for acquiring the force data could be improved so as not to produce so much vibration.

3.7.4 Deformation

The deformation displayed around the pad at each speed is shown below in figure 3.17. This visualization shows the increase in deformation experienced as the ball velocity increased. This is expected as the material needed to deform to a greater degree in order to reverse the direction of the faster travelling ball.
Generally the results indicate that a greater deformation was experienced at the top of the pad at all three speeds, this is possible as the pad is thicker in these sections closer to the knee, also higher levels of compression were experienced by the pad at higher impact velocities.

### 3.7.5 Discussion

One of the main advantages of this experimental setup was to use a representative mass and velocity of impactor in order to simulate more closely the strain rates of impact experienced during a game situation as previously discussed. Calculating the exact strain rate of each of the materials within the pad is complex, but by treating the full thickness of the pad as an isotropic homogenous material this greatly reduces the difficulty of the calculations and allows an average strain rate experienced by the materials to be determined.

Using equation (3.3) for a definition of strain rate. We also know that we can calculate strain as:
\[
\varepsilon = \frac{\Delta l}{l} \quad (3.8)
\]

Where \( l \) is the total thickness of the foam sample, which is found by measuring the thickness of the pad at the impact position. \( \Delta l \) is the change in thickness, or is the same as the deformation calculated from the high speed video footage. Also from the high speed video footage a measurement for the time to maximum deformation can be found and used as \( dt \) in an approximation of strain rate by combining equations (3.3) and (3.8) to give:

\[
\dot{\varepsilon} = \frac{\Delta l}{l} \frac{1}{dt} \quad (3.9)
\]

On inspection of several of the videos, the following ranges for strain rate were calculated.

- 31.31 m/s, strain rate in the region of 400 s\(^{-1}\) - 600 s\(^{-1}\)
- 22.36 m/s, strain rate in the region of 300 s\(^{-1}\) - 450 s\(^{-1}\)
- 13.42 m/s, strain rate in the region of 180 s\(^{-1}\) - 250 s\(^{-1}\)

It is estimated that the strain rate of the British Standard test would be lower still. It has been previously discussed how the results vary with impact velocity, and therefore strain rate so in order to build up a true picture of the pads performance it is at these higher strain rates that testing needs to be carried out.

The major drawback within this work was the noise within the system used to measure the force, which lead to error. A Kistler model 9067 quartz piezoelectric force transducer was used to take the force readings in combination with a leg shaped anvil mounted to the front. With this setup, there were vibrations within the equipment, which affected the reliability and validity of measurements taken. This was a weak point within this testing procedure and in order to create a better representative test for cricket a different system for measuring the transmitted force should be used.
3.8 Conclusions

A laboratory based system for testing cricket leg guards under game specific conditions has been established. A ball is fired at equivalent bowling velocities towards the leg guard mounted on a leg shaped anvil using an air pressure regulated ball canon with variation of less than 3.2%. A hockey ball is used to give greater repeatability for impacts. Transmitted force values were measured using a force transducer and using high speed video cameras measurements of COR, deformation and contact time were taken with less than 7% variation from the mean.

The results demonstrated that there is variation in performance of a single leg guard over the single specified area of protection according to the British Standard in all measured variables. The results also show an inter-relation between the measured variables and the pads ability to dissipate force. The main outcome of this experiment was that the system of force acquisition is inadequate for measuring these high energy short duration impacts and an alternative should be found.
4. Design of a Force Acquisition System for High Energy, Short Duration Impacts

Chapter 3 reported a method of testing cricket leg guards under conditions that approach those experienced when they are used in a game situation. The experiment showed a quantitative test with representative ball mass and velocity can be possible. One shortcoming of the method was the ability to acquire accurate force data. The purpose of the following chapter is to introduce a novel method of force acquisition, which is specifically designed for these high energy, short duration impacts. A discussion of how this system may be incorporated into a representative cricket leg guard test is also included. This is followed by a discussion on calibration of the system and an estimation of the error present.

4.1 Introduction

In Chapter 3 it was established that the standards used for testing PPE may not be testing the equipment appropriately. For example, a recommendation for an increase in the tested force level for the British Standard test for football shin guards was proposed by Ankrah and Mills (2002) after closer inspection of that standard. This may not mean that the protection specified is inadequate but the premise for the level required is unclear and it may place an unnecessary barrier to design innovation.

The strain-rate dependence of polymers was also discussed and given as a further reason why representative testing was needed. Although the exact strain-rates of the British Standard test and a cricket ball impact during a game have not been calculated, comparison of the speeds of the impacts, a 2.5 kg mass impacting at 5.65 ms\(^{-1}\) compared to a 163 g ball impacting at over 30 ms\(^{-1}\), should indicate that the pads will be compressed at different rates. By testing the cricket pads at a non-specific strain rate it is possible that the protection of any incorporated foams may not be comparable to the protection afforded under game conditions.

The aim here is to create a testing procedure for a cricket leg guard that is more representative of the conditions experienced under a game situation. This was attempted in Chapter 3, but a limitation was found
in the accuracy of the force measurement system. To improve this, a novel concept for measuring the force in high energy, short duration impacts is researched.

4.2 Alternative measuring system

The most common method of measuring an applied force is to mount the impacted object rigidly on a force transducer and apply the load. If the system is made significantly rigid and the natural frequencies of the system are sufficiently high, then the measured loads are likely to be representative of the applied load. Often system rigidity can be questioned and a rigid system is also not representative of the human supporting the cricket pad.

It is possible to calculate the force applied to a rigid object by knowing its mass, the magnitude of any other external forces on the mass, and by measuring the acceleration of its centre of mass. Newton’s second law can then be used to find the imposed force. This principle has been applied to the development of a force acquisition system suitable for use during short duration impacts.

Measuring the acceleration of the centre of mass of an object might be achieved in several ways:

1- by mounting an accelerometer at the object’s centre of mass

2- by drilling a hole to the mass centre so that a non-contacting device such as a laser Doppler vibrometer (LDV) can be used to measure the acceleration of this point

3- by measuring the acceleration of points either side of the centre of mass and averaging this value (figure 4.1).
The linear, $a$, and rotational, $r$, accelerations in each direction and about each axis can then be found using the following equations:

\[
\begin{align*}
a_x &= \frac{a_5 + a_6}{2} \\
a_y &= \frac{a_3 + a_4}{2} \\
a_z &= \frac{a_1 + a_2}{2} \\
r_x &= \frac{a_3 - a_4}{l_{34}} \\
r_y &= \frac{a_1 - a_2}{l_{12}} \\
r_z &= \frac{a_5 - a_6}{l_{56}}
\end{align*}
\]

Where $l$ is the distance between the two accelerometers. These equations are only valid for small angles of rotation and if the pairs of linear accelerometers are positioned equidistant either side of the axis of symmetry.

The mass can be effectively freely-suspended by using light springs or bungees and attaching it to an external frame. This requires aligning the bungee attachments at right angles to the impact direction so that the anvil mass becomes quasi-freely-suspended, there is no resistance to movement in the impact direction.
for small displacements. As shown in equation (3.5), the stiffness and mass of the system affect its natural frequency, but in this system, all the bungees are pulling at right angles to the force applied from the impactor (figure 4.2), and the stiffness, $k$, becomes:

$$k = k_{\text{bungee}} \times \cos 90 = k_{\text{bungee}} \times 0 = 0$$

(4.2)

Figure 4.2 – Illustration showing the impact direction perpendicular to the force of the bungees on a square plate anvil

Therefore at the point of impact, the stiffness of the system is independent of the mass and tends to zero, so the natural frequency will also tend to zero. This means there will be no extra oscillations caused by vibration related to the natural frequency of the system, leading to a very “clean” force profile even at low contact times.

The natural frequency of the force transducer need not be considered through the use of this method but the anvil itself still has a natural frequency that could be excited. Struck in the centre, a freely suspended rod can begin to oscillate about this point, which is depicted in figure 4.3. The first longitudinal natural frequency, $f_n$, of a rod of length, $l$, density, $\rho$, and Young’s Modulus, $E$, when struck was given by Bayon et al. (1993) as:

$$f_n = \frac{1}{2l} \sqrt{\frac{E}{\rho}}$$

(4.3)
These oscillations can be avoided through careful anvil design and avoiding long thin shapes will keep the first natural frequency high. It is also possible to calculate this value and compare it to the expected contact time to ensure it is sufficiently high so that these frequencies are not excited.

Consideration of the stiffness of the bungees holds less importance. At the point of impact the bungees are perpendicular to the applied force from the impactor, so the rig has negligible stiffness. For impacts with a large contact time the anvil and impactor will travel whilst in contact with each other. This will stretch the bungees and cause a retarding force vector to be applied to the anvil. The contact time can be increased if a large amount of deformation occurs, or if the impactor mass is not considerably lower than that of the anvil. Having the mass of the anvil considerably greater than that of the impacting object is an important requirement of the system as it ensures clean separation of the two objects leading to a clearer measured force profile. Estimates for contact time can be calculated by considering a rigid body collision of two free bodies. The braking effects of the bungees on the anvil throughout longer duration impacts can be calculated by simply resolving the forces applied by the bungees to find the magnitude of the retarding force on the anvil throughout the impact. Any objects attached to the anvil of significant mass, for example a cricket leg guard, are included in the system mass used to calculate the force.

4.3 Anvil design

The anvil in the rig serves several purposes. It mimics the shape of a player’s leg, it is an attachment point for the cricket pad and it provides a leg mass to be accelerated. It is also important that the mass of the anvil is much greater than the mass of the impactor. This allows the two masses to separate quickly after impact as the lighter impactor effectively rebounds off the significantly larger anvil.
The anvil was designed utilising a simple cylinder of diameter 100 mm and length 130 mm. The dimensions were based on the dimensions of a player’s leg, and also to allow attachment of the cricket leg guards. A 5th percentile UK male calf radius is 51.2 mm, and 95th is 70.0 mm (Peebles & Norris, 1998), these measurements are taken at the widest portion of the calf and so the majority of the lower leg is smaller than this. When strapped to the anvil, the leg guard will have a similar radius of curvature as to when it is attached to a human leg, this creates the initial static strain in the pad prior to impact which it would be under on a player’s leg. The anvil is not attempting to mimic a leg except in its dimensions; it gives a rigid surface from which meaningful force data can be taken. The anvil was machined from a single piece of steel to maximise its stiffness and avoid any vibrations. Initial calculations estimated the first longitudinal natural frequency at over 2 kHz, or a period of under 0.5 ms. The anvil had a mass of 7.73 kg, this was the lightest the anvil could be made given the dimensions and available materials. This made it sufficiently heavier than the 163 g hockey ball to allow a short impact duration but also light enough that the bungee system could still support it. There are various cut-outs from the final anvil design which can be seen in figure 4.4. This was to allow the accelerometers to be recessed so that they would not be damaged by ball impacts.
Figure 4.5 – Diagrams detailing a top down view of a) the ideal anvil and b) the altered anvil showing their ability to deal with edge impacts

The optimum design would have the force applied from the bungees coincident with the anvil's centre of mass. Due to the design of the cricket pad being tested, and the requirement of testing positions over its entire outer surface, the pad would need to be rotated around the anvil to allow impact with edge positions. Figure 4.5a) shows the problem that this can cause if the bungee runs through the centre of mass, the amount that the pad can rotate is limited and the edges cannot be impacted. This was solved by running the horizontal bungee through an eyelet off the back of the anvil, the attachment points on the external frame were offset the same distance so that the bungees were still perpendicular to the impact direction, figure 4.5b) and 4.6.

The accelerometers used were the 4375_V from Bruel & Kjaer, (Bruel & Kjaer, 2011) which are recommended for use in shock and vibration analysis and have an operational frequency of between 0.1 Hz and 16500 Hz. Six single axis accelerometers, mounted in pairs equidistant from each of the centroid axes as in figure 4.1, were recessed into the anvil to protect them from rebound impacts. Figure 4.6 shows the final anvil design; the cut-out sections used for recessing the accelerometers can be seen on the top, side
and back of the anvil. Matching cut outs were made on the bottom of the anvil to maintain the mass centre close to the geometric centre. Similarly, cut-outs were made on both sides of the anvil, despite the accelerometers only being positioned on one side. Sections of material were also removed from the front of the anvil to balance the loss of material from the rear, to maintain a smooth curve for impacting; the material from the front was removed from the top and bottom of the anvil’s front surface.

![Photo of the final anvil attached to the bungee system](image)

Figure 4.6 – Photo of the final anvil attached to the bungee system

The accelerometers were run through Nexus charge conditioning amplifiers and the data captured by National Instruments Data acquisition hardware (National Instruments, 2011), connected to a laptop running Smart Office software. This allowed immediate display of the force data, before saving and exporting for full analysis in Matlab. The resulting force was calculated using Matlab software, the acceleration pairs were averaged using equations (4.1), to get three independent linear accelerations, these vectors were then summed and using the mass of the combined anvil and leg guard system a force trace was derived and plotted, an example of a resulting force profile is shown in figure 4.7. The 6 individual acceleration profiles were also plotted to allow inspection at this stage for any anomalies or fluctuations that may be relevant but hidden through further processing. Data were sampled at 25.6 kHz for a period of 0.32 seconds; a 10% block pre-trigger was used to ensure all data was captured consistently.
The bungees used to suspend the anvil were 16 mm diameter and their stiffness is inversely proportional to their length. When strained in tension on a 5569 Instron tensile testing machine testing machine at 100 mm/min, the 1 m lengths of bungee were found to have a linear stiffness of approximately 115 N/m beyond a strain of 20%, figure 4.8. These bungees attached the anvil to a custom built frame within the protective enclosure of the air-cannon under a strain of 20% to utilise the linear portion of their stiffness. The ends of the bungees were attached to loops on the anvil and their ends crimped, a similar method was used to attach the bungees to the external frame. For the test of the leg guards, preliminary testing showed the displacement of the anvil to be negligible. This resulted in minimal retarding force applied by the bungees; therefore no resolution of forces was required to account for this error.
4.4 Calibration

Before the use of this system, a form of calibration was carried out to ascertain whether the designed system was working to measure the forces and to what degree of accuracy. The method of calibration was carried out at force levels and contact times similar to those experienced during testing in order to be relevant. The following section describes the method of calibration used and relates this to the accuracy that can be expected from the results.

The method for calibrating the system was to use an impact hammer to strike the anvil. The force impulse of the hammer could then be compared to the measured force trace from the accelerometer system for accuracy of measurement. This was a simple and repeatable test and valid as long as the peak forces and impulse times were similar.

A standard force hammer, weighing 0.5 kg, was found not to be capable of generating sufficient force, therefore a custom hammer was fabricated utilising a Brue and Kjaer 8230-003 force transducer mounted
onto a 1.5 kg in-house manufactured hammer, depicted in figure 4.9. The 350 mm long shaft was topped with a 200 mm cylinder with a 25mm diameter to form the hammer structure constructed from steel. The increase in mass meant that the peak forces were closer to the cricket ball and pad impacts.

![CAD image of the custom impact hammer with force transducer attached](image)

*Figure 4.9 – CAD image of the custom impact hammer with force transducer attached*

Using this setup, three impacts were carried out with each of the three different available tips, steel, nylon and silicone and the accelerations were recorded for each. The different tips were used to create different contact conditions, the most rigid steel causing shorter contact times and higher peak forces than the softest, which was silicone, with nylon falling in the middle. The 3 measured accelerations in x, y and z directions were analysed using Matlab as detailed in section 4.3 to find the force. An example graph showing the input force trace of the hammer with a silicone tip and the measured force trace of the anvil is shown below in figure 4.10.
Across all 9 impacts the biggest discrepancy for any single impact was just under 4% of the total force measured. For both the steel and nylon tips, the difference was under 2.3%, but these values were increased for the silicone tip. This was likely to be due to deterioration of the silicone tip during the impacts, energy from the impact caused permanent plastic damage to the tip causing a discrepancy between the input and measured force signals. The silicone tip impacts showed contact times of 3 ms and peak forces of approximately 4 kN which were sufficiently close to the expected values of the ball on cricket pad impacts to safely claim that uncertainty in the measurement system would be less than 4%.

Figure 4.10 - Graph showing the measured force profile compared to the input force profile
Using the measured force data from each accelerometer individually, the power spectral density (PSD) found using the Matlab function (Appendix A). This code was used to analyse the vibration within the system, an example of one of the graphs produced is shown in figure 4.11. The PSD for this purpose gives an indication whether vibrations are occurring within the anvil and if so at what frequencies. It can be clearly seen that there are clear frequency responses at 15 kHz and at 25 kHz, which may cause interference with measurements around those frequencies. Final contact times within the representative test are given later in section 6.3.3 but represent contact times of between 3 ms – 8 ms, this correlates to frequencies of 125 Hz – 333 Hz, an area of the PSD where there is no natural frequencies of the anvil to interfere with force measurement.

4.5 Baseline Impacts

Preliminary testing was carried out using the new anvil being impacted by a hockey ball fired at 31.29 m/s (70 mph) with no cricket pad attached. This demonstrated the force applied by the hockey ball impacting the rigid steel anvil. It also established a base line to derive how much protection was provided by the cricket leg guards and gave evidence of the repeatability of the results obtained from the system. This series of impacts
will give a force trace of higher amplitude and shorter duration than would be expected during pad testing so demonstrates the systems functionality even under extreme testing protocols. Three impacts were carried out, and the force data, sampled at 5 kHz, is shown below in figure 4.12.

![Figure 4.12 – Force against Time for three impacts carried out at 70mph on the un-protected anvil](image)

The results show that the procedure was repeatable even under these extreme conditions, with three impacts producing a peak force of between 11 kN and 12 kN, a contact duration of between 1.0 ms and 1.2 ms and the gradient of the up and down slopes demonstrate good repeatability. These values can be compared to the results of testing on cricket leg guards to give a clearer indication of their efficacy in reducing impact forces and the mechanism by which they achieve this.

### 4.5 Conclusions

In conclusion, the aim of this chapter of developing a force acquisition system more appropriately designed for measuring the force of high energy short duration impacts was successful. Its accuracy during calibration testing has been demonstrated as having less than 4% uncertainty along with its ability to measure high energy impacts of short duration without distorting the signal with excessive noise.
In order to integrate this method of force acquisition into a representative test for cricket, a final design for the anvil was developed; this takes into account the requirement for re-positioning the pad for some positional impacts and incorporates the horizontal bungee attachment to the rear of the anvil. Consideration was also given to bungee stiffness and the positioning of the accelerometers. The anvil was also tested for performance at conditions above and beyond what a leg guard would be expected to perform under and has proven its functionality.
5. Cricket Leg Guards and Benchmarking a Representative Test

In Chapter 3 an initial attempt at creating a representative test for cricket leg guards has been reported, although, since it lacked the ability to measure the force profiles accurately, in Chapter 4 a new system of measuring the force data was developed, to be incorporated into the representative test. The following chapter performs an analysis of the structure of the three selected cricket leg guards in order to best decide the impact positions to be tested with the representative test. A pilot study measuring impact characteristics of a cricket ball on a pad worn by a player is also carried out in order to identify the values for contact time, deformation and COR which would be encountered during a game, these values could then be used to quantify the accuracy of the final representative test.

5.1 Introduction

Despite the relatively small number of changes that have been observed in the last 100 years (section 1.2) in the design of cricket leg guards, there has been little effort to establish the protection levels afforded by these pads in a meaningful way. The construction of three modern cricket pads is analysed within this chapter to compare how they differ from each other but also to establish where they should ultimately be tested using the representative testing protocols, both to give a good representation of their overall protection but also to ensure any weakness’ are highlighted.

The only recognised means of testing for these pads is the British Standard (BS 6183-1:2000 and 6183-3:2000), although there are separate standards for cricket helmets in Australia and New Zealand (Satra, 2011). As discussed previously (Chapter 2) the British Standard requires cricket protective equipment to be tested utilising heavier impacting implements and much lower impact speeds which do not accurately replicate the impact conditions experienced during a game though they do provide a standardised means of testing which is necessary for comparison of products. The work carried out in this thesis aims to establish a testing protocol that more closely represents the impacts that the PPE will undergo during a game situation. In order to do establish how well this has been achieved, the game specific impact must be quantified for
comparison with the representative test. Within this chapter, a pilot study is conducted to measure the following three variables (discussed further in section 3.2.3) during an impact under game conditions:

- Contact time – the time the ball and pad are in contact measured from high speed video footage
- Deformation – the maximum distance that the ball displaces into the cricket pad after first contact, also measured graphically off high speed video footage
- Coefficient of Restitution (COR) – ratio of outbound to inbound velocity of the impactor, determined from velocities calculated from high speed video measurements

Results from this work can then be used to quantify how closely the impacts carried out during the final representative test come to impacts under game conditions, and thus how truly representative the testing protocol is.

5.2 Analysis of Cricket Pad Structure

The structures of three cricket pads were analysed in order to determine the impact locations for dynamic testing. During the analysis of the cricket pad structure both the aesthetics of the pad and the “in game” functionality were considered. Destructive analysis was also carried out in order to gain a better understanding of the mechanisms used to prevent injury. Consideration of the aesthetics of the pad may not seem relevant to the impact characteristics, but was important to understand whether the protection of the pad had been compromised by the aesthetic design. Throughout this section, a lot of the information presented represents an engineers’ initial impressions and opinions on the pads analyzed. This style is used to contrast perceptions of the pads with their quantitative performance measurements.

5.2.1 Introducing the Cricket Leg Guards

Three cricket leg guards were selected for analysis; one set which represents the majority available on the market based on the same traditional cane-based construction that has already been discussed (section 1.2). The other two were selected to represent design variations that are displayed in a smaller range of commercially available leg guards, more details on reasons for selection are given below.
Cricket leg guard 1 (pad 1), figure 5.1, represented a modern version of the “traditional cane based pad”. The pad has the traditional longitudinal rolls, which in older pads would have contained the canes running continuously from the bottom of the knee roll to just above the ankle. These rolls are split into three sections suggesting that a continuous cane is not used and giving the pad a more modern appearance. The pad has traditional style three roll knee protection, containing some detail where the roll appears to be split towards the outer edges. The lower thigh protection at the top of the pad, again resembles the traditional shape of older pads, but has additional shaping of the protective materials to form a pattern.

The interior face of the pad is representative of a standard leg guard. Behind the knee roll, there is additional padding stitched into the pad. This material is considerably softer than the outer materials to allow a comfortable fit. Additionally there is a removable section of the softer foam that runs down the front of the shin and can be repositioned. The softness of the foam gives a more comfortable feel against the player’s leg and the ability to adjust its position allows the player some level of customisation to attain the fit he feels is best. It is anticipated that this insert is provided primarily for comfort rather than impact energy dissipation. The pad as a whole is held on the leg using a three-strap velcro attachment system, one at each the bottom and top of the calf and another higher up which runs directly behind the knee.
Figure 5.2 - Cricket Leg Guard 2 a) exterior face and b) interior face

Cricket leg guard 2 (pad 2), figure 5.2, maintains some of the traditional shape and style of a cricket pad, the pad contains a single area of protection for the lower limb and an additional piece to protect the thigh, along with the same three strap attachment system as most pads. There is no longitudinal cane structure, no knee roll and fewer external features and rolls covering the pad surface. Pad 2 displays some of the same foam shaping used in pad 1 to provide a more attractive pad. These appear on the central shin section of the main pad and also on the outside edge. Both these areas would be expected to take more direct impacts so whether extra protection is provided by these additions would be interesting. Similar detailing is included on the thigh protector section, though this appears to serve more of a decorative role.

The interior of pad 2 has two additional sections of padding which are customisable in position, this is achieved by removing each section and replacing it in the desired position on its hook and loop attachment point. One provides softer foam to cushion the knee itself and the other is a much more robust section to give fit and comfort to the shin. The ability to reposition both of these sections allows the player to create a more comfortable fit for themselves. The shin section is akin to a common football shin guard with stiff plastic outer and softer foam toward the player. Pad 2 also uses the same three Velcro strap attachment system used with pad 1 to attach it to the players leg, but a greater initial curvature of the pad around the player’s leg means less force is required from the straps to bend the pad around the leg and ensure a secure fit.
The design of cricket leg guard 3 (pad 3), figure 5.3, steps away from traditional design with a simpler engineered solution; this leg guard is designed to conform around the leg, and extends around both the inside and outside of the lower leg much further than the other two pads. This conforming fit allows the pad to be held in place by only two straps instead of the three used on pad 1 and 2.

Pad 3 has a single piece plastic shell formed over a one-piece moulded foam inner. On the interior a thin piece of soft foam is included to provide a more comfortable fit to the shin. This pad is considerably lighter at 514 g, than the other two being tested, pad 1 being 817 g and pad 2 being 825 g. The entire surface of the pad is smooth except on the inner edge where there is an angular edge, which can be seen in the cross-section view, figure 5.4. The aim of this is to give more control to the rebound direction of the ball. It also gives a straight edge that the side of the bat can sit against and prevents any gaps that a ball can pass through. On the underside of the pad there is a vent to allow air in and out of an air-cavity between the hard outer and foam protection. The use of this air-cavity is an additional novel feature of this alternative design of cricket pads.

The picture shown in figure 5.4 is taken from the manufacturer's website and shows an example cross-section of pad 3 when impacted by a ball. It shows the air-cavity compressed by a ball impact and indicates
that there is another piece of material used to give the straight edge greater rigidity. This is claimed to give more control of the balls rebound (Aero, 2012).

![Hardened Edge](image)

**Figure 5.4 – Cross-section of cricket pad 3**

### 5.2.2 Destructive Analysis

The internal construction of the pad was analysed by dissection. Wherever possible, only the stitching used to hold the pad together was unpicked so as not to damage any of the inner materials. By analysing the materials used and their lay-up, the mechanisms of force dissipation could then be approximated. In each figure the pads are displayed with the outer most layers of protection furthest to the left and working inwards towards the right.

It should be noted that this section represents one person’s opinion and is given as explanation and to support decisions taken later. As such the exact identities of each of the included foams was not required as the general feel and appearance of the material properties only was required to form an opinion on the protection afforded. Below is a general description of each of the foams identified in the various constructions, the foams have been designated as low, medium, high or very high density based on their feel in the hand:

Foam (A) is a medium density white foam similar to ethylene vinyl acetate foam (EVA) which makes up the majority of the first 2 leg guards.

Foam (B) is a medium density foam similar to (A) though does not recover its original shape as quickly

Foam (C) is medium density but used in only very thin sections and is encased in the middle of the pad.

Foam (D) is a low density foam used to give a more comfortable fit.

Foam (E) is a high density foam used throughout pad 3 as the primary source of protection.

Foam (F) is a very highest density foam, nearly a solid plastic and used as a reinforcing structure.
On internal inspection, the following sections and materials were identified within pad 1, figure 5.5:

1) Thin sections of foam (A), should provide force reduction for thigh protection and to provide design detail on the pad front.

2) Packed wool, would appear to give less force reduction but provides a different texture under pad 1’s logo in a less important zone of protection.

3) The protection over the knee is provided by densely packed wool fibres, there are also thin sections of foam (A) to provide further impact protection and give a distinct shape to the front section.

4) Small sections of foam (A) give protection to the cane structures underneath, this may help to protect the canes and stop them fracturing. There are also sections of this foam used to give higher protection levels to the ankles and outer shin area.

5) Foam (B) provides the majority of the foam and thus the protection for the thigh.

6) Two thick sections of foam (A) are layered to provide protection for the inner shin area.

7) Cane sections are sandwiched between two sections of cardboard with a thin layer of foam (C) behind them. The cardboard may act to prevent splinters of cane passing through to the players’
leg and the foam gives a forgiving feel to the inside of the pad. The canes act to reduce spread 
the impact force over a larger and reduce the pressure on the cricketers’ leg.

8) Covering the inner ankle, there is a section of foam (A) with the end of a cane behind it and a 
piece of foam (B) behind that. The ankle has one of the thickest layers of foam protecting it.

9) Two sections of foam (B) sit loosely over the back of the caned section; they not only provide 
protection but also create space to allow greater deformations of the pad.

10) A combination of wool stuffing and a thin section of foam (A) fill the section behind the logo 
situated in the central section just above the foot cut-out. This section is also covered with a 
stiffer plastic material, different from the white faux leather used elsewhere.

11) The internal padding of the knee consists of three sections of foam overlaid on each other, glued 
together to form one piece. Both Foam (A) and foam (B) are used here, along with Foam (D), 
this is all encased in a light, breathable fabric.

12) Layers of Foam (B) and (D) are used here again encased within the light breathable fabric to 
prevent heat build-up against the player’s leg.

This analysis highlighted the complexity of this pad design. There are multiple areas on the pad that might be 
required to provide the same level of protection but that are constructed in very different ways. The main 
example of this is the central shin and outside shin regions. The central shin has many differing layers of 
foam and the inclusion of canes, whereas the outer shin uses no canes but just several thick layers of Foam 
(A). Both areas could experience the same impact conditions yet they would have to limit the peak force 
using different mechanisms.

The use of canes in the design allows the impact force to be distributed up and down the pad. This does not 
necessarily reduce the total force, but reduces the pressure on the players’ leg; it also increases the area of 
foam over which the force is applied, meaning there is more foam to absorb the energy. If no canes were 
used, it is hypothesized that higher pressures would be generated over a smaller area around the impact 
region. In order to reduce the transmitted force in this case, the thickness of the foam would need to be 
increased. Spreading the force should allow a greater force to be dissipated with a thinner layer of foam 
material.
Figure 5.6 – The internal construction of cricket pad 2

Following the same procedure, figure 5.6, the structure of pad 2 was analysed as follows:

1) Thin sections of foam (A), provide force reduction for thigh protection and to provide design detail on the pad front.

2) Similar to the thigh protector, thin sections of foam (A) are sewn on to the outer material to provide strategic increases in protection and give design detail.

3) Two thick sections of foam (A) are shaped and glued together to maintain their curvature.

4) The main body of the pad is formed from two thick sections of foam (A) that are glued together.

5) An additional piece of foam (B) is used behind the pad section providing additional padding at the ankle.

6) Foam (D) bulks out the inside of the knee area with its softer feel providing a comfortable fit whilst small sections of foam (A) give further protection.

7) Sections of foam (A) form a small inner shin guard protected by a layer of stiff plastic (A), this section alone may provide considerable protection.

8) A single strip of foam (D) provides a comfortable fit against the leg.

Pad 2 has a considerably simpler design than pad 1. It utilises fewer components and materials, and the use of the same foam based construction throughout would be expected to give a more consistent protection
level and consistent impact and rebound characteristics throughout. Specific areas of interest for testing would be to see whether the extra foam sections included on the exterior of the pad for detail in sections 1) and 2) provide any significant further protection, and also whether the lack of a knee roll compromises protection around the knee.

The majority of the outer protection of pad 2 is foam, this means there are no specific structures to spread the force over a greater area and suggests that the primary method of protection be energy absorption. The only material stiff enough for its primary role to be to distribute the force is on the underside of the pad incorporated into the shin guard piece. This section also incorporates stiff and soft foams so the force reduction properties of this section alone were investigated.

![Figure 5.7 – Internal construction of cricket pad 3](image)

Analysis of the materials and construction of pad 3, figure 5.7, found the following:

1) High density foam (E) outer gives a smooth outer surface and stiffness to the pad

2) High density foam (F) insert along the inner edge, gives stiffness to the edge and also formed one side of the air-cavity.
3) Closed cell Polyethylene, a medium density foam formed the majority of the protection

4) Inside the pad a section of antibacterial polyester fabric provides a comfortable fit with negligible contribution to protection

By matching the curvature of a players leg this pad does not need the lateral flexibility required of the previous two. This allows the exterior shell to be made of a stiffer covering which is likely to be effective in distributing the force in two dimensions across the surface instead of just one as is likely to be the case with the canes.

5.2.3 Impacting Positions

Following analysis of the external and internal constructions of the three cricket leg guards, an informed decision was made as to which positions should be impacted during the dynamic testing. These positions were selected to give a good representation of the protection provided by each pad. This section presents the positions of impact (figure 5.8, 5.9, 5.10 and 5.11) with accompanying tables giving reasons for the selection of each position. The system of selecting test positions to highlight possible weaknesses within the leg guard was the method used in the British Standard (BS 6183-3:2000) and relies on the testers knowledge and experience. Other impacting positions are selected to highlight positions of high protection or to characterize large areas where the protection is similar.
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<tr>
<td>1</td>
<td>Used with 4 to see effect of extra padding at ankle</td>
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<tr>
<td>2</td>
<td>Protection afforded by different construction</td>
</tr>
<tr>
<td>3</td>
<td>3, 7 and 10 give effect of extra foam sections, and with 4 to see effect of cane</td>
</tr>
<tr>
<td>4</td>
<td>Compared with 1 to see effect of extra foam</td>
</tr>
<tr>
<td>5</td>
<td>5, 6, 8 and 9 gives pattern of protection across shin with canes</td>
</tr>
<tr>
<td>6</td>
<td>5, 6, 8 and 9 gives pattern of protection across shin with canes</td>
</tr>
<tr>
<td>7</td>
<td>3, 7 and 10 give effect of extra foam sections</td>
</tr>
<tr>
<td>8</td>
<td>5, 6, 8 and 9 gives pattern of protection across shin with canes</td>
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<td>9</td>
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<td>10</td>
<td>3, 7 and 10 give effect of extra foam sections</td>
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<tr>
<td>11</td>
<td>Gives protection for lower knee</td>
</tr>
<tr>
<td>12</td>
<td>Gives protection for side of knee</td>
</tr>
<tr>
<td>13</td>
<td>Gives protection at upper knee position</td>
</tr>
<tr>
<td>14</td>
<td>Gives protection for thigh at central position</td>
</tr>
<tr>
<td>15</td>
<td>Gives protection for thigh at side position</td>
</tr>
<tr>
<td>16</td>
<td>Protection afforded by different construction</td>
</tr>
</tbody>
</table>

**Figure 5.8** – The proposed positions to be impacted shown on cricket pad

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87
<table>
<thead>
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<th>Position</th>
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</thead>
<tbody>
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<td>1</td>
<td>1, 2 and 3 give the protection afforded by the lower section of the pad</td>
</tr>
<tr>
<td>2</td>
<td>1, 2 and 3 give the protection afforded by the lower section of the pad</td>
</tr>
<tr>
<td>3</td>
<td>1, 2 and 3 give the protection afforded by the lower section of the pad</td>
</tr>
<tr>
<td>4</td>
<td>4, 7 and 10 give the central most padded region protection and how it changes up the pad</td>
</tr>
<tr>
<td>5</td>
<td>5 and 9 give the protection of the extra foam section on the side compared to 6 and 8</td>
</tr>
<tr>
<td>6</td>
<td>5 and 9 give the protection of the extra foam section on the side compared to 6 and 8</td>
</tr>
<tr>
<td>7</td>
<td>4, 7 and 10 give the central most padded region protection and how it changes up the pad</td>
</tr>
<tr>
<td>8</td>
<td>5 and 9 give the protection of the extra foam section on the side compared to 6 and 8</td>
</tr>
<tr>
<td>9</td>
<td>5 and 9 give the protection of the extra foam section on the side compared to 6 and 8</td>
</tr>
<tr>
<td>10</td>
<td>4, 7 and 10 give the central most padded region protection and how it changes up the pad</td>
</tr>
<tr>
<td>11</td>
<td>11, 12 and 13 represent where a traditional knee roll would be and plot the protection in this area</td>
</tr>
<tr>
<td>12</td>
<td>11, 12 and 13 represent where a traditional knee roll would be and plot the protection in this area</td>
</tr>
<tr>
<td>13</td>
<td>11, 12 and 13 represent where a traditional knee roll would be and plot the protection in this area</td>
</tr>
<tr>
<td>14</td>
<td>14, 15 and 16 plot the thigh protection of this pad, 14 is in between the sections of extra padding</td>
</tr>
<tr>
<td>15</td>
<td>14, 15 and 16 plot the thigh protection of this pad</td>
</tr>
<tr>
<td>16</td>
<td>14, 15 and 16 plot the thigh protection of this pad</td>
</tr>
<tr>
<td>17</td>
<td>Gives the protection of just the underside section</td>
</tr>
</tbody>
</table>
5.3 Pilot Study to Benchmark Cricket Ball Impacts on a Player

Discussion so far has centred on developing a testing procedure representative of the impacts occurring during a game situation. There are no data within the current literature describing any parameters of game related impacts for cricketers, therefore in order to establish how closely a new test represents a game impact some of these parameters need to be measured.

It is the purpose of the section to define the parameters of the impact of a cricket ball impacting a leg guard worn by a player; this will represent a game specific impact as closely as possible. In this section the contact
time of a cricket ball when impacting a pad worn by a player will be measured to allow a benchmark for comparison with the representative test to be carried out in Chapter 6. In addition, measurements of COR, deformation and the players perception of when an impact becomes too uncomfortable were taken. In the impact tests on an anvil, a hockey ball was used for repeatability but within this test to make the conditions as close to a game as possible, a cricket ball is used.

When designing a representative test for cricket leg guards, many of the major variables are easily defined, such as the mass and velocity of the ball. However, the influence of a human leg on the overall impact is unknown, and there have been no studies reported in the literature regarding this. In order to provide repeatable impact conditions and to ensure that only the influence of the protective equipment is measured, a rigid leg was specified. It is important to quantify the effect this has on the specificity of the test.

### 5.3.1 Test Design

The test used required the player to wear each of the three pads in turn to face balls from a mechanical bowling machine at increasing speeds up to 35.76 m/s (80 mph). This speed represents the high end of ball velocity experienced by batters as observed by Abernethy (1981) who measured the ball release speeds of high level bowlers and the speed at which they reached the batter. A player’s skill level is unimportant in this test as they were not required to move.

*Figure 5.12 – Picture showing a batsman facing the BOLA machine (Bola, 2008)*
The BOLA is a mechanical bowling machine used by players to practice batting without a bowler (figure 5.12). It uses two horizontal counter-rotating wheels that are speed adjustable. The ball is fed in between the wheels, which launch the ball towards the batter at a pre-selected speed. Normally the BOLA is mounted on long legs to represent the release height of an average bowler, allowing the ball to be played after contact with the ground. In the arrangement used here, the BOLA was repositioned in order to allow the ball to impact the player without bouncing. The position of the machine increased the repeatability of the impact location and also allowed the speed of the impact to be more closely controlled, as the unpredictable effect of rebounding off the ground was eliminated, figure 5.13.

![Diagram of BOLA](image)  
*Figure 5.13 – Picture showing the experimental setup for the player testing*

The BOLA was initially configured to launch the ball at 13.41 m/s (30 mph). One impact was carried out on each set of pads in the central shin section, before increasing the speed in 4.47 m/s (10 mph) increments up to a maximum of 35.76 m/s (80 mph), 6 speeds of impact on each pad. The BOLA has an LCD readout displaying the programmed ball speed, but it is important to calibrate these to find the actual ball speed before starting the experiment. The calibration was completed using the same Photron SA1 fastcam high speed video camera to record the flight of the ball fired at various speeds from the BOLA at 10,000 fps. The flight of the ball was digitally analysed using Image Pro Plus, BOLA ball speed was adjusted until the digitised speed matched the required value measured from the high speed video. The central shin section was used for impacting as this is the main section facing the ball delivery so is most likely to receive a normal impact in a game, it also has the thickest area of padding so should result in the least discomfort for the player. One impact was observed at each speed to minimise player discomfort, but to allow crude feedback to be gathered. Subjective discomfort was measured through instant opinion, by starting at the
slowest speed and building up, it allows the player to be aware of when an impact may become too uncomfortable, and testing can be halted.

The impact was filmed perpendicular to the ball delivery and in line with the front pad at 10,000 frames per second. The batter assumed a forward defensive position and allowed the ball to strike centrally on his pad. A forward defensive position is effectively a lunge, where the front shin is vertical or slightly tilted forward, a common position used by players in a match. The high speed video was analysed afterwards using Image Pro Plus software to take measurements of the inbound and outbound velocities, the deformation of the pad and the contact time of the ball. Due to the minimum height of the BOLA being at 1.70 m high, and the slight forward lean of the pad in the forward defensive position, the ball was effectively striking at an angle down the pad where in a game it would be closer to a normal impact. To alleviate this discrepancy, all impact velocities were measured normal to the pad face from the high speed video footage using a similar system to that discussed in section 3.6.1.

5.3.2 Results

Subjective discomfort was measured through the opinion of the batsman, using a pass-fail criterion of whether he deemed the discomfort level to be acceptable or not, taken immediately following each impact. Discomfort became unacceptable for pad 3 on the 5th impact suggesting that a threshold of tolerance had been exceeded. The normal inbound velocity of this impact was measured at 28.43 m/s (63.60 mph); this is lower than the expected value of 31.29 m/s for that impact, due to the angle between the pad and the balls flight. This is a ball speed that could reasonably be expected to be encountered during a game situation. It is unclear whether this discomfort would be accepted by an elite player, or if it was excessive, but as this was not encountered with either of the other leg guards it was concluded that the level of protection afforded by pad 3 is likely to be the least effective of the three being tested. The three variables measured for each of the pads are discussed below.

The results are presented with the marker representing the measured value and error bars showing the maximum variability of each variable when taken from video footage as found in section 3.6. The variability in impact velocity measurement is not shown as considered negligible at less than 1%.
Figure 5.14 shows the measured contact times of all three pads. Impacts with pad 3 exhibit a consistent contact time across all speeds of impact of around 7 ms to 8 ms. The contact times of the other two pads vary from 7 ms to 15 ms. With a rigid anvil instead of a fleshy leg, the contact time would be expected to be lower than this value. With the majority of the impacts recording contact times of between 7 and 12 ms, this would be the range of values expected in an ideal representative impact test.
Figure 5.15 displays the measured deformation experienced by each pad at each impact speed. Despite the varying construction and thickness of the three tested pads, there is a general trend for the deformation to increase as the ball speed increases. The impact position coincides with the tibia bone that runs down the front of the shin, therefore all of this deformation is likely to be in the pad and not in the leg. It is possible some deformation may occur in the tibia itself, but its stiffness relative to the cricket leg guard is high, and any impact severe enough to cause tibial deflection would be expected to cause excessive levels of discomfort, which only one of these impacts did. Deformations of between 45 mm to 75 mm were recorded at representative bowling velocities so similar values would be expected during a representative test.
The effect of normal impact velocity on the coefficient of restitution of the three pads is shown in figure 5.16. The COR for pad 3 appear to stay relatively constant with a range of less than 0.07 across all impact speeds encountered. Both pads 1 and 2 show a considerable drop as the speed increases down to minimal values of 0.14, although both these pads do show a considerable degree of variation even at similar speeds. Overall, a value of between 0.14 and 0.32 would hope to be observed during testing, though this value may vary due to the interaction of several factors including the stiffness of the anvil, where the ball impacts, the pad construction and the surface friction interacting with the spin of the ball.

5.3.3 Discussion

The purpose of this testing was not to determine the detailed performance of each leg guard, but to establish a testing envelope within which the proposed representative testing apparatus should operate across the range of possible commercially available constructions.

The consistency of launch provided by the BOLA machine is a limiting factor in this experiment. The aim was to impact two thirds up the central shin portion of the pad, in the centre. During the experiment, any impact which was off-centre or too high or low, then the impact was repeated. Issues were also apparent with off-
centre strikes, the ball would then tend to roll around the leg and lead to measuring an increased pad deformation due to the position of the camera when this was not the case, figure 5.17. Again this was eliminated as far as possible by repeating the measurement for poorly directed impacts.

Despite evidence that would suggest that current pad performance is adequate, shown by the absence of lower leg impact injuries reported in the literature (Orchard et al., 2006, Finch et al., 1999, and Stretch et al., 2005), testing was halted with pad 3 due to discomfort caused to the player. The discomfort was deemed excessive by the player, but it is possible that this impact did not cause enough damage to be deemed injurious within the literature. This could suggest that either cricket leg guard protection is not adequate or that pad 3 represents a leg guard capable of passing an equivalent kinetic energy test but not performing adequately during a game situation.

Figure 5.17 – Illustration of the effects of an off-centre impact during cricket pad testing
5.4 Conclusions

The three cricket leg guards to be tested were introduced and a full analysis of the structure of these pads was carried out. The position of impact test sites for each of the three leg guards has been identified and the rationale given. In addition, the pilot study looking at cricket ball impacts to cricket leg guards whilst mounted on a players’ leg identified ranges for these human related impacts. Contact times of between 7 ms – 12 ms, deformations between 45 mm – 75 mm and COR values of 0.14 – 0.32 were measured and represent the values that would be expected to be encountered during a true cricket game impact.
6. Benchmarking Performance of Cricket Leg Guards

Having designed a testing procedure for cricket leg guards, based on matching the impact velocity and mass of the impactor and utilising a rigid anvil to measure transmitted force, this chapter utilizes this method to benchmark the performance of three cricket leg guards under this new representative test. The aim of this chapter is to benchmark cricket leg guard performance and to establish quantitatively how close the representative test is to the game impact and whether this needs to be improved.

6.1 Introduction

The aim of the laboratory based dynamic testing procedure was to accurately mimic the impact conditions experienced by personal protection equipment when used in a game situation.

The representative test presented in this chapter matches the mass, velocity and physical properties of the impactor and the boundary conditions of the anvil closely (section 1.5). The physical characteristics of the impactor and anvil encompass not only the material properties of the structure but also its size and shape. Indirectly, the shape of the force profile, including the contact time and peak force, along with other parameters such as coefficient of restitution and degree of deformation are likely to be the same.

The physical characteristics of the anvil will affect the contact characteristics of the impact and the impactors outbound velocity. In a game of cricket, the anvil is the cricket players lower leg. This being the case, and the mechanical properties of a steel anvil and a human leg being different, it is important to quantify the difference this makes. Reference values for a cricket ball on human impact have been found in Chapter 5, so a representative test for cricket can now be carried out. This test will look at cricket leg guard performance under representative conditions but also how close the representative test approaches a game situation impact.
6.2 Methodology

The experimental setup used for this work is similar to that used for the initial high speed cricket pad testing in Chapter 3 (section 3.3), except that the fixed anvil and load cell were replaced by the freely suspended force acquisition system developed in Chapter 4, using the same setup detailed in section 4.3. A schematic of the experimental setup is shown below in figure 6.1.

![Diagram of the experimental setup](image)

Figure 6.1 - Schematic of the experimental setup

The positions to be impacted are shown in figures 5.8, 5.9 and 5.11. Each of these sites was impacted 3 times at 31 m/s (70 mph) normal to the pads surface and the acceleration was measured in the 3 axis directions. The selected impact velocity was 31 m/s to simulate release speeds of bowlers of up to 35 m/s (80 mph), based on work on release speeds of elite bowlers by Abernethy (1981) and taking into account the 14.3% loss in speed of contact with the playing surface as reported by Penrose et al (1976). Time between repeated impacts, although not recorded, was kept consistently around 2 minutes due to the time required to reset the measuring equipment. This time period is longer than the recommended ICC regulations (ICC Handbook, 2012), which suggests a minimum of 15 overs should be bowled per hour, or 40 seconds per ball.

After the equipment was setup as shown in figure 6.1, the high speed video camera was checked and calibrated. The air pressure on the canon was altered until the required speed of 31 m/s was achieved consistently, the speed being checked with the high speed video footage. The first cricket pad was attached to the anvil with the first impact aligned with the ball cannon, the first impact was carried out with the high
speed video and accelerometer data being recorded. Between impacts the measurement equipment was reset allowing a recovery time of 2 minutes between repeated impacts. This process was then repeated 3 times at each impact location on each of the three pads.

For each individual impact the peak force value was calculated using Matlab software following the same method as detailed in section 4.3. For each impact inbound and outbound velocities along with contact time and deformation data were derived from video recorded by a Photron SA1 Fastcam recording at 10,000 fps and the video was analysed using Image-Pro Analyzer software. A mean value was then taken for each set of three impacts at a particular location for each variable.

These values were then used to construct a spatial distribution of each parameter across the surface of the leg guard, illustrated using a colour plot. Each of these colour plots is displayed and discussed in section 6.3. These are accompanied by contour plots of the range of values found at each position, these give an indication of how consistent the trends discussed are. The maximum values for the range scale were set manually, at one third of the maximum measured value for the respective variable. This allowed comparison between the different parameters and comparison of their reliability as well.

To generate the colour plots in the following sections, in turn for each measured variable, the mean value of the three impacts were calculated and plotted at their relative position on the cricket leg guard within an excel spreadsheet. Linear interpolation was then used to fill the spaces between these known values thus creating a full field of numbers which could be imported into Matlab and the colour plots generated.

### 6.3 Results

The results of the representative impact testing for cricket leg guards is presented and discussed below.
6.3.1 Peak Force

Figure 6.2 – Peak force distribution (top) and range (bottom) for the three tested cricket pads
The distribution of the measured peak forces across the surface of the three cricket pads (figure 6.2) follow a similar pattern. Lower peak forces are measured towards the centre of the pad on the regions that cover the central shin and knee, the measured values then increase towards the edges of the pad. This correlates with the perceived needs of players reported by Webster (2010) where he discussed the desire for more padding in this central region as this is where the most substantial normal impacts would occur, and both pad 1 and pad 2 demonstrate this. Similar levels of protection are afforded by both pads, indicated by the peak transmitted force values, but the area of most protection in pad 1 is centred more on the knee and upper part of the shin whereas the major protection of pad 2 stops short of covering the entire knee region but does extend further down the shin. The areas where the peak forces are lower are the areas of the pad that are physically thicker with more padding built in.

The lowest peak forces were measured in pad 3 corresponding to the stiffened edge designed to control ball rebounds. This area has been identified in the structural analysis, section 5.2, as being thicker and having an extra wedge of foam in order to reinforce it. The main aim of this area is to control the rebound direction of the ball but it also creates an area of high protection. The peak forces across the central shin of pad 3 were actually measured to be 30% higher than those of the other two.

A general trend across the three impacts at a single site was for the peak force value to increase. This may have occurred as the materials did not have enough time to fully recover from the previous impact or because the leg guard became permanently damaged. This would require further investigation, but as the time period between impacts is longer than the time between balls in a match, these results could be prudent. This is also displayed in the range of the results. The knee region on pad 1 shows the highest variation between the three readings and also coincide with the use of wool stuffing as the main padding material, instead of the foam based materials which form the majority of the padding elsewhere which show lower variations.

The range of the measured results has created an interesting pattern. Pad 3 has a generally lower range which indicates that the materials used in its construction stands up better to repeated impact than the others or has a quicker recovery rate. For both pad 1 and 2, the position where the range is greatest coincides with the areas of lowest peak force transmission. This suggests that although these areas are giving the highest levels of protection their performance is also deteriorating the quickest, which is backed up by considering
the individual force readings taken for each impact shown in table 6.1 below, where the increase in peak force is 62.3% for pad 1 and 97.8% for pad 2. This degree of deterioration in performance may be temporary or permanent damage sustained by the pads but shows that use of more appropriate materials could lead to a better performance under repeated loadings.

<table>
<thead>
<tr>
<th>Impact (N)</th>
<th>Pad 1 (Position 13)</th>
<th>Pad 2 (Position 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact 1</td>
<td>5814</td>
<td>3415</td>
</tr>
<tr>
<td>Impact 2</td>
<td>7125</td>
<td>4375</td>
</tr>
<tr>
<td>Impact 3</td>
<td>9439</td>
<td>6755</td>
</tr>
<tr>
<td>Percentage Increase</td>
<td>62.3%</td>
<td>97.8%</td>
</tr>
</tbody>
</table>

*Table 6.1 – Table showing each measured peak force values for the successive impacts*
6.3.2 Coefficient of Restitution

Figure 6.3 – Coefficient of Restitution distribution (top) and range (bottom) for the three tested cricket pads
The COR is a ratio of the inbound and outbound velocities, so, when squared becomes a ratio of the inbound and outbound kinetic energies. In this experiment the inbound energy is constant so COR can be an indicator of the energy dissipated by the leg guard. The change in COR over the three pads’ surfaces (figure 6.3) correlates with the distribution of peak forces. Where the peak forces were lowest around the central knee and shin regions, this is also where the lowest COR values are measured. This is understandable as force, f, and energy or work done are related simply by the equation:

\[
\text{Work done} = f \times d \tag{6.1}
\]

Where \( d \) is the distance moved in the direction of the force, which would be equivalent to the deformation of the leg guard. This shows there is an inherent connection between the peak force, the COR and the measured deformation. The lower peak forces are measured in the areas with physically thicker padding which gives more material under the impact to absorb energy and thus the lower COR values.

An interesting point is the higher COR values recorded on pad 3 overall when compared to the other two. This could be to do with the different construction and materials used in cricket pad 3. Stiffer foams with less hysteresis (section 1.7) will dissipate less energy resulting in higher COR values, but pad 3 also has the more rigid outer shell covering which could contribute to this as well. This is despite pad 3 not recording generally higher peak force values, suggesting that the energy is being stored and released back elastically rather than being dissipated.

A similar pattern emerged regarding the ranges as was the case for the peak force measurements, a high range in COR coincided with the positions where the lowest COR values were measured. These are also the areas where the foam padding layer was thickest, so this could be why there is a greater deterioration in performance. Also, pad 3 has overall smaller values for the range, again suggesting a more consistent performance of the materials over successive impacts.

There are some large range values shown on the left of the colour map for pad 1. This position would represent the inside of the player’s front leg, an area where the player is less likely to be struck by a forceful impact. As previously discussed, the structure here is different to that on the outside of the shin. It is possible that this difference in construction has contributed to a greater deterioration in performance and thus the larger range.
6.3.3 Contact Time

Figure 6.4 – Contact time distribution (top) and range (bottom) for the three tested cricket pads
The contact times of impacts against the three pads (figure 6.4) show a similar pattern to the previous two variables. The areas with the greatest thickness of padding have the lowest peak forces, lowest COR values and now are shown to have the highest contact times. It follows that a higher contact time will give the materials of the pad more time to absorb the energy of the impact thus reducing the peak transmitted forces and reducing the outbound energy of the object.

Overall the range of values displayed for the contact time is low, indicating the consistency of this variable. Each of the pads shows elevated ranges for this variable in the areas where the peak values are highest which fits with the trends we have seen with the other measured variables for similar reasons. There is one area on the left side of pad 2 that shows an unanticipated high value. The high range here can be traced back to the original reading where it is just the final impact that has a significantly lower contact time. The ball speed for these impacts was then examined and for this third impact, the ball cannon has had a minor fluctuation and projected the ball at a higher velocity than the other two tests. This higher velocity caused the lower contact time and thus the increased range. This result has not been removed to highlight the need for a real-time read-out of ball velocities, but also as the contact time initially did not appear erroneous.

Similarly there is one point along the identified ridge of extra padding on pad 3 where there is also a greatly increased range. This is a region where a slight change of position of impact can make a huge difference in the measurements due to the quickly changing structure of the pad across small areas. All three values of contact time are different and it is assumed that the positioning of the pad for impact was not as accurate as required leading to the marginally different pad constructions being tested in the area causing the variation in measured results.
6.3.4 Deformation

Figure 6.5 – Deformation distribution (top) and range (bottom) for the three tested cricket pads
The final variable, deformation (figure 6.5), follows a similar pattern as the previous three, suggesting that the four measured variables all correlate, at least for each pad independently. The areas of greatest deformation are the knee and part of the shin area for pad 1, the central shin region for pad 2 and the rebound controlling ridge for pad 3. In general the lower degrees of deformation are exhibited in the thinner areas of the pad and the larger numbers in the thicker areas; this infers that under these protocols the pads are being tested at near full compression with each impact. The range of values is very low across most positions on all pads, which would also suggest this. If the padding materials are nearly bottoming out on each impact then there is little room for variation.

A higher range of values is displayed on the thicker region of the knee on pad 1 and the rebound controlling ridge on pad 3, indicating that maybe these thick areas were not fully deformed but did sustain damage in initial impacts leading to subsequent impacts with more deformation and thus to a higher value for the range.

Around the ankle regions for pad 1, higher range values are measured where there are no rigid canes supporting the thin padding. The knee region of pad 2 shows the highest region of variability in terms of the range across the three pads, this can be traced back to the air cannon, again delivering a fluctuation in delivery velocity, this has led to a higher peak force but a lower than expected deformation. It is possible that a velocity fluctuation combined with a human error in placing the pad may have caused this increased range.

### 6.3.5 Trends

In addition to evaluating each resulting variable individually, there are two main trends that run throughout the data that are to be discussed. The first is the link between peak force and contact time. Figure 6.6 shows the peak force plotted against contact time for every impact on each of the three pads. The R-squared value, a measure of the correlation to a defined trend, was found using the inbuilt function in Excel. The values for the trend corresponding to each pad respectively are 0.69, 0.86 and 0.81, where a value of 1 represents a perfect correlation. Pad 2 and pad 3 both have high R-squared values indicating a strong correlation between these two variables. Pad 1 has a distinctly lower value and this can be linked to the use of different materials for different areas of the pad, each will have a slightly different relationship between contact time and peak force so causes a global lowering of the correlation for the whole pad.
Figure 6.6 – Graph of peak force against contact time for every impact on the three leg guards

Figure 6.7 below displays the contact time plotted against the deformation for every impact on the three pads, R-squared values for the three pads are 0.87, 0.73 and 0.79 respectively. These numbers indicate a strong overall correlation between these two factors, especially considering this is every impact carried out on all the differing positions across each pad.
These trends suggest that by increasing the thickness of a given pad, this will allow an increase in deformation. The increased deformation will lead to an increased contact time and thus a lower transmitted peak force. These two trends indicate that the primary method of lower peak force in the pad observed during this testing is by direct absorption of energy into the foams. Further investigations, which measure pressure distributions, may be able to identify the influence of load spreading but this is beyond the scope of this work.

### 6.3.6 Discussion

Assuming a lower transmitted peak force value is representative of a higher degree of protection, it is clear that varying levels of protection are afforded across the surface of the leg guard. The highest amount of protection is provided on the central shin region and on the knee roll. These are the areas where normal impacts would be most likely to occur. As the batter moves his leg towards the line of the ball to play a shot, it is these central regions that line up with the balls trajectory. It has also been shown by Webster (2010) that protection in this region is most important to the player. Impacts to outer regions will tend to be oblique impacts as these areas curve around the sides of the leg and are not aligned with the balls flight whilst a
skilled batsman plays a shot. There is also more protection on the outside of the shin than the inside as it is the outside of the shin that is closer to oncoming balls.

As each impact site is tested multiple times, a reduction in the protective qualities of the pads over these repeated impacts has been shown by an increase in the transmitted force values measured. The exact mechanism for this is unknown and probably varies across the three pads due to their differing constructions. Some of the reduction in protection will come from the materials being compressed and not fully returning to their original dimensions before a repeated test, a degree of hysteresis remaining within the structures, these reductions may decrease if the pads were given longer to recover between impacts. These impacts are high energy and highly compressive, so plastic deformations in the foams are also likely to occur. These would permanently damage the materials and cause a reduction in performance over the entire life of the garment.

There are limitations to this testing method. The accelerometers are set up to measure the acceleration of the anvils’ centre of mass, however once a pad is attached to the front of the anvil, this position moves. During the impact, the ball also becomes part of the system, and the centre of mass moves again. Throughout the impact, the pad is compressing, and as such the centre of mass is constantly moving its position within the anvil. The accelerometers are therefore only actually measuring the acceleration close to the centre of mass throughout the impact. The mass of the anvil is far greater than the mass of either the pad or the ball, therefore it can be calculated that the additions of these two objects to the system does not move the centre of mass more than 1 cm. As the anvil is effectively rigid, any deformations will be small, particularly towards its core where the centre of mass is, this should mean that the difference between the measured acceleration and the actual acceleration at the centre of mass is likely to be negligible. Within the time frame of this impact, the distance travelled by the anvil is less than 1mm, therefore, the braking forces exerted by the bungee can be neglected.

Of significant importance in demonstrating the efficacy of this testing method is the clarity of the force trace. The three impacts at position 6 are shown overlaid in figure 6.8. This is the raw, unfiltered data multiplied by the constant value for the mass to give a force signal. There is minimal noise and disruption to the signal despite the high peak forces and low impact time. This figure also makes the effect of multiple impacts clear. Each consecutive impact has a steeper gradient and reaches its peak force sooner during the impact. It also
climbs to a higher peak force value. This would indicate that with repeated impacts in the same position the player would be at increased risk of injury.

![Graph showing force-time data for the three separate impact at position 6](image)

**Figure 6.8 – Graph showing force-time data for the three separate impact at position 6**

Two other issues that have been highlighted through this work are the minor fluctuations in ball velocity and the human error of pad placement. Due to the sensitivity of the measuring equipment used small velocity fluctuations and their effects are easily identifiable in the results. This problem is due to the way the pressurized air cannon works to project the ball, in order to improve this one option would be to implement a more reliable ball launcher, but there will always be some variation particularly at the high speeds used in this work. Alternatively an accurate method of taking real-time ball velocities would indicate whether the results of an impact are worth saving or not. Human error of pad placement may be helped with a laser sight to help line the ball up with the cannon instead of carrying out the task by eye (section 3.4) but this would only help minimize and not eradicate this issue.
6.4 Quantifying Representative Test Accuracy

One of the aims of the work reported in this chapter was to quantify how close the proposed representative test approached actual player related game impacts. The values for contact time, deformation and coefficient of restitution were measured for a ball on pad impact when attached to a human leg in section 5.3. Looking at just the measurements taken correlating to representative bowling impact velocities, reference ranges from this experiment are shown in table 6.2. These values are then compared to the values taken from the benchmark testing of the 3 cricket leg guards for the same position:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Player measured range</th>
<th>Benchmark test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Time (ms)</td>
<td>7 – 12</td>
<td>3 – 4</td>
</tr>
<tr>
<td>Deformation (mm)</td>
<td>45 – 75</td>
<td>45 – 52</td>
</tr>
<tr>
<td>COR</td>
<td>0.14 - 0.32</td>
<td>0.38 - 0.50</td>
</tr>
</tbody>
</table>

Table 6.2 – Table of reference ranges for human related impacts and benchmarked values

The contact time of the benchmark test is approximately 50% lower than that measured in human tests. As previously discussed, this is due to the rigid anvil being stiffer than a human leg. The human leg will also deform along with the pad increasing contact time.

The deformation experienced across the impacts on the three pads has a lower range for the benchmark tests that falls within the range of measured player test values. The reason the bottom end values are not as low in the benchmark test is due again to the rigid anvil creating a more severe impact by making the pad the only deformable object. Inversely, higher degrees of deformation are seen at the top of the range of the player test as the human leg may begin to deform in addition to the pad.

The COR values are higher when the leg guard is mounted to the anvil rather than a players leg. This is again due to the influence of the rigid steel anvil, the deformation of the human leg is dissipating some of the impact energy and slowing the balls rebound velocity whereas mounted to a steel anvil, the leg guard itself cannot absorb as much energy so the ball rebounds at a higher velocity.
The new representative testing protocol is an improvement over previous testing methods in terms of matching energy and momentum of the impactor and thus replicating game conditions more closely. Generally the contact times, deformation experienced and COR values measured are all of similar orders of magnitude to those that would be experienced during a game situation. It is clear that the major source causing the discrepancies is the steel anvil not mimicking the human leg accurately. By re-designing the anvil and making it biofidelic, it is possible that these results may be matched more closely but this would negatively affect the ability to measure transmitted force. The anvils’ primary purpose was to measure the transmitted force values accurately, and this is then used as indicator of the level of protection provided by the leg guard. A full investigation into the effects of introducing a biofidelic anvil and how closely the human testing data can be approached would be of interest but is beyond the scope of this project. The developed test represents the closest a realistic in-game impact can be modeled without compromising on the accuracy and repeatability of the force measurements, and has prioritized the most important aspects of producing a representative test impactor mass and velocity (section 1.5). This representative testing protocol represents a major step forward in terms of the ability to test cricket leg guards under game situation impacts and the ability to design them specifically for their protective task.

6.5 Conclusions

The work within this chapter was initially concerned with using the freely suspended force acquisition system, designed in Chapter 4, as part of the representative test for cricket leg guards. It details the quantitative analysis of the three selected leg guards, in terms of their ability to reduce transmitted force but also in investigation of the mechanisms by which they achieve this. It is clear that although a minimum performance standard is employed, the performance of the leg guards tested under this protocol vary when exposed to impacts using game specific masses and velocities. This is indicated by variations in peak force of over 30% and variations in contact time, COR and deformation of 3 ms - 4 ms, 0.38 - 0.50 and 45 mm - 52 mm respectively. Overall the work presented demonstrates the ability to quantitatively measure dynamic impacts with game specific masses and velocities.

The outcome of the work completed in this chapter was to establish quantitatively how closely the representative testing protocol used to benchmark cricket leg guard performance is to the actual game
impacts. Although the primary variable, peak force, could not be measured, the other three variables of deformation, COR and contact time were all of the same order of magnitude but contact time was 50% of the value taken during human trials and COR was around double. This was the closest the numbers could be matched under game conditions without sacrificing the accuracy and reliability of the measurements taken and by maintaining the correct mass and velocity of impactor. This representative testing protocol represents a significant step forward in terms of the ability to test cricket leg guards under game situation impacts.
7. Representing a Human Sports Impact Kick

Due to the full contact nature of the competitive matches within taekwondo, functional protective equipment is a necessity. Despite the obvious requirement for engineered protective equipment, the current designs are basic and the testing procedures used to measure their performance bear little resemblance to the impacts that the garments would be subjected to in a match situation. This chapter identifies the types of impacts that may be encountered and presents arguments of relevance when considering a testing procedure to mimic these. It follows the design process of creating a mechanical simulator to recreate particular impacts and suggests methods for tailoring the system for a closer match.

7.1 Introduction

Taekwondo is a Korean martial art and is also the national sport of Korea. In Korean tae means “to strike or break with foot”, kwon means “to strike or break with fist” and do translates simply as “way” or “method”. A rough literal translation is that taekwondo is “the way of kicking and punching”. Despite this translation the emphasis in taekwondo is firmly on kicking, as the longer more powerful legs allow greater damage to be caused to an opponent from the furthest distance away, therefore minimising the possibility of successful retaliation.

One of the most popular systems of taekwondo is named after the organisation that sets the rules for competition, the World Taekwondo Federation. The WTF rules are used in the Olympic Games, with sparring consisting of three, full contact, two minute rounds with one minute breaks. Points are awarded for permitted damaging blows to the designated scoring areas, light contact does not score. Scoring techniques include punches to the body and kicks to the body or face (WTF, 2009).

WTF taekwondo sparring is full contact, this makes it as close to a real fight as possible, the techniques are practiced at full speed and full force. The result being that should the techniques be required for self-defence then no alteration will be required to the execution. It is the full contact nature of the style that means the competitors require significant protective equipment to prevent serious injury. Within the rules the competitor is required to wear a head protector, a groin guard, forearm guards, shin guards, gloves, a mouthpiece and a
trunk protector or hogu. The hogu not only provides protection but also gives a visual indicator of the scoring zones and differentiates between the two competitors, figure 7.1.

![Image of Taekwondo Hogu](image)

*Figure 7.1 – Picture showing the taekwondo hogu*

The hogu provides protection for the upper body of the contestant but a method of testing its performance in a way representative of the conditions it experiences during a taekwondo match is not currently available. Within the following chapter this problem is addressed by development of machine capable of recreating these conditions.

### 7.2 Kicking in Taekwondo

Player testing is widely used in the development of new sports equipment. Athletes’ perceptions and feedback is useful during the design process but throughout a series of tests the athlete is liable to tire and provide an inconsistent performance. During human evaluation of golf club performance, Suzuki and Ozaki (2002) found that this evaluation technique requires many trials because weather conditions and physical condition of the golfer at the time of testing greatly affected the distance of the hit ball. The solution to athlete inconsistency and fatigue is to use a mechanical simulator. Mechanical simulators are now widely used to provide accurate and repeatable impacts.
Specific work on the repeatability of humans kicking a target was carried out by Tsui (2011), it was established that even for highly skilled practitioners, hitting a target multiple times and specifically at a high level of force was inconsistent. Figure 7.2, has been adapted from Tsui’s work and shows the variability within kicking for University level competitors in taekwondo. Seven competitors were used and each completed 70 front leg roundhouse kicks in sets of 10. The first 10 were to be as consistent as possible, the next 50 were randomly assigned as either fast or hard once the previous kick had been completed, the final 10 were then to be consistent as possible again. The individuals kicked a Body Opponent Bag (BOB) martial arts trainer which had a hogu fitted and a Tekscan pressure measurement system attached to the front, as shown in figure 7.3. Participants were required to aim for the centre of this. Force, contact time impact location and impact velocity was measured. The ability of competitors to kick the marked impact location was found to be poor. Tsui measured force, but then normalized this by the athlete’s weight and a leg length to height ratio that was constant for each participant using the equation below:

\[
\text{Normalised force (N/kg)} = \frac{\text{Absolute force/weight}}{\text{leg length/height}}
\]
Kicks were normalized against that participants fastest recorded kick to form a decimal value of their quickest measured speed. This work demonstrated that should a human be used to test the protective equipment, not only would the impacts be inconsistent in both force and velocity (figure 7.2) but also in position.

It is possible that by choosing a push type kick, that the impacts may have been more accurate, as the kicker could aim at the face-on target more easily, but a similar variation in peak forces would still be expected. These findings agree with that of Suzuki and Ozaki (2002), that a human cannot reproduce speed and force inputs under fatigue. For a repeatable impact, this process needs to be automated through the design and manufacture of a kicking robot designed for this purpose.

In taekwondo there are many different types of kicks and punches used in attack and defence, each uses a differing technique to transmit forces to the recipient in different ways, in different amounts of time and from different angles. The most commonly used techniques include the front kick, side kick, roundhouse, axe kick, hook kick, back kick and the spin kick. Other techniques are also used, and several of these kicks may be linked in combinations with spins and jumps to create effective attacks. Each of these kicks may also have different names and slight variations on the technique performed. In general the kicks can be separated into two classes, the push kicks and the swing kicks. The push kick action of the leg is similar to a piston being...
driven linearly towards the opponent, where the swing kicks will generally keep the leg straighter and more rigid and the velocity is created by swinging the leg around their body. Using the push kicks, the fighter can put more of his body mass into the kick and increase the energy of the impact, but they are also more easily blocked due to their linear straight-at-the-fighter nature.

It has been established that the roundhouse kick is the most commonly used kick during competition (Lee, 1983). The roundhouse is also a powerful scoring kick directed predominantly at the athletes’ torso, the area protected by the hogu. Using this kick as a benchmark means the hogu will be tested at a high level of force allowing sufficient protection for lower level attacks. The roundhouse is also one of the most studied kicks in the literature, and is similar across several martial arts.

Figure 7.4 – Photograph showing the position of a fighter at impact whilst executing the roundhouse kick
(TKD Quebec, 2009)

Figure 7.4 shows the finishing position of a roundhouse kick. The roundhouse kick has been defined as a flexion/extension motion of the knee with a flexion of the hip joint combined with a simultaneous rotation of the trunk and hip joint abduction (Lee and Ricke, 2005). The hip joint of the support leg rotates externally to facilitate the rotation and kicking action. Abduction of the legs involves them moving away from the bodies centre line laterally, and flexion of the hip would involve decreasing the angle between torso and thigh. This kick is the most commonly used as it is a quick kick with high levels of power.
In order to evaluate the performance of the taekwondo hogus in a representative way, a system must be created to mimic the kicker and recipient system as a whole. Due to its prevalence during competition bouts and the research already carried out the roundhouse kick has been chosen to be mechanically simulated to be used during benchmark testing. Development of such a system represents a novel undertaking as no known system to replicate this has ever been developed.

7.3 Introduction to Mechanical Simulators

A mechanical simulator is required to mimic the force production from a roundhouse kick in a repeatable manner. The complex nature of the human movement means that it is not a simple movement to replicate. There is no literature detailing the design of a mechanical simulator to replicate the motion of a martial arts kick. There are several examples of mechanical simulators that were used to mimic the action of kicking a football. If we compare the biomechanical description of a roundhouse kick given above with the description of a mature kicking action in football we can see many similarities. Wickstrom (1975) detailed the football kicking action as being initiated by bringing the kicking leg back while the leg flexes at the knee, forward motion then begins by rotating the pelvis around the support leg and bringing the thigh of the kicking leg forwards while the knee continues to flex. After this initial phase the thigh begins to decelerate as the shank is vigorously accelerated to full extension at ball contact. It was also noted by Lees & Nolan (1998) that the leg remains straight through ball contact. Essentially these two kicks from different sports are similar except for the hip abduction exhibited in the roundhouse, so a study of the work done to mechanise the kicking action in football was decided to be constructive.

There is one major difference between the kick in football and the roundhouse in taekwondo, and that is the angle of the leg to the body. In football, the leg is aligned under the body at contact with the ball. This means that the range of motion permitted by this kick to build up foot velocity is limited by the flexibility of the hip flexor muscles. By drawing the leg back and upwards quickly, a stretch reflex can be initiated in the kicking legs hip flexors and used to accelerate the leg more quickly. In taekwondo, the leg is abducted so that at contact the stance leg and striking leg are approximately 90 degrees from each other.
An example of a mechanical simulator that attempted to mimic the human motion of a football kick is the ‘Roboleg’, which was described by Schempf et al. (1995). This robot attempts to replicate each of the leg segments and joints to reproduce the kinematics of a human kicking the ball, figure 7.5 above. The foot, shank, thigh and hips are all represented and each joint was given a realistic range of motion except the torso rotation, extra rotation allowed a build up of speed similar to a running kick in football. The leg was manufactured at a reported cost of $400,000 and initially displayed good results with foot speeds of up to 20 m/s, ball velocities of 40 m/s, a good level of accuracy when shooting and high repeatability. However, the machine is now not operational and is displayed in the adidas museum in Germany after a multitude of problems including gear mesh failures and motor overheating.

adidas manufactured a machine, the ‘Robbie leg’ which is a simplified version of the biomechanical events that take place. This system uses two pneumatic pistons with the leg suspended between them, figure 7.6. The suspended leg has a pivot which should allow the leg to bend and act like a human leg, but is not driven like the ‘Roboleg’ so should not have the same mechanical problems. This is a much simpler design but suffers in reliability due to the pneumatics and has difficult reaching high ball velocities. This mechanical
simulator focused more on the outcome of the movement, matching the characteristics of a foot kicking a ball but only at the point of impact.

Holmes (2008) examined the design of a soccer/rugby ball kicking robot. He took the advantages of both these previous robots to create a successful solution. By using the mechanical simplicity of the ‘Robbie leg’ along with the accuracy and reliability of an electric motor control system, he designed a robot capable of producing repeatable impacts, figure 7.7. Rather than try and mimic the whole kicking action, the focus is on matching the launch characteristics of the ball. Ideally this would include the moment of inertia of the leg as a whole, the stiffness of the joints as well as the foot velocity, but by focusing solely on the foot velocity a robust repeatable design has been manufactured. The kick may not match the mechanics of a human, but provides an accurate and repeatable impact condition.
All three of these mechanical simulators could be adapted so as to function as a taekwondo kicking simulator. To decide which represents the best option for design, a decision matrix is used. The factors considered are:

- The repeatability of the impact, the capability of the machine to produce the same programmed impact over and over
- The reliability of the simulator, the lower the likelihood of a mechanical failure the better
- The ability to manufacture within the time frame of this project

Each of these are weighted with a factor between 1 and 3, the ability to manufacture being the most important, the repeatability of the impact second most and finally the reliability. Each of the possible concepts was then rated from 1 to 3 for each criteria, then the rating and weighting were multiplied. The results of this analysis are shown in table 7.1 below:
Table 7.1 – Decision matrix for concept design of mechanical kicking simulator

From the decision matrix, it is clear that the most successful is the design by Holmes. It has had good success at recreating kicks and is still functional, it emphasizes the importance of matching the impact motion and not the human motion in a repeatable way and most importantly is capable of being manufactured within the scope of this project. In producing a test for taekwondo protective equipment, the aim is not to mimic what the action looks like, but to replicate the outcome of a roundhouse kick. The finishing position of the roundhouse kick is shown in figure 7.4. Despite the complex actions leading up to the point of contact, now the kicking leg is nearly straight and moving in an arc around the vertical axis of the support leg. It is possible to simulate this with a driven rotating rigid leg.

7.4 A Mechanical Simulator for Taekwondo

Using the most successful football mechanical kicking simulator as a concept, an initial design was developed of a taekwondo mechanical kicking simulator. This design is based on the same principles as the football mechanical simulator designed by Holmes. It uses a reliable electric motor to drive a rigid kicking leg, in order to approximate the impact conditions. Design of a kicking robot is a complicated task and this design has proven the most successful for football and rugby kicking actions of the few attempts that have ever been made. By mounting the motor vertically and the kicking leg horizontally the action of the robot leg resembles the spinning action of the roundhouse kick.
In order for the impact to be representative it is important to match the characteristics highlighted in section 1.5. The primary variables are the velocity and inertia of the kicking leg at impact, after these come the contact time and force profile. The force profile of a human on human impact will be influenced by a number of factors, the mass and inertia of the kicking leg, the speed of the impact, the stiffness in the joints of the contacting foot and leg and the stiffness of the body being impacted.

The key component for this design is the specification of the motor, in the following sections, a series of first approximations are made to develop this. In order to specify a motor, first approximations need to be made as to how heavy the leg will be, how fast it will need to be moving at impact and how quickly it will need to accelerate to reach these criteria. Once a motor is selected, then detailed design of the impacting leg and support frame can be developed.

### 7.4.1 Impact Velocity

A number of studies have been completed which examine the impact velocity of roundhouse style kicks in martial arts. Lai and Wei (2002) reviewed the literature to compare with the results of their experiments, the results they collected are shown in table 7.2, these sources were also checked before inclusion. The values given are the means of the peak velocities achieved throughout the experiments. The average peak velocity for these experiments is around 15 m/s, but design of the robot should allow operation at above 18 m/s to match the extreme loading conditions.

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Expertise</th>
<th>Mean peak linear velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conkel et al. (1988)</td>
<td>Elite males and females</td>
<td>14.6</td>
</tr>
<tr>
<td>Serina &amp; Lieu (1991)</td>
<td>Male black belts</td>
<td>15.9</td>
</tr>
<tr>
<td>Pieter &amp; Pieter (1995)</td>
<td>Elite males</td>
<td>15.54</td>
</tr>
<tr>
<td>Pearson (1997)</td>
<td>Expert males</td>
<td>13.4</td>
</tr>
<tr>
<td>Lai &amp; Wei (2002)</td>
<td>Singapore National males</td>
<td>18.0</td>
</tr>
</tbody>
</table>

*Table 7.2 – Table of mean peak velocities at point of impact during a roundhouse kick observed in the literature (Lai & Wei, 2002)*
7.4.2 The Mass and Inertia of a Kicking Leg

Anthropometric data supplied by Tsui (2011), table 7.3, details both the total mass of the leg and also the mass of the bone separately for 50\textsuperscript{th} and 95\textsuperscript{th} percentile adult males. Pain and Challis (2006) demonstrated that soft tissue motion has a significant impact on ground reaction forces during drop landings. Essentially the bony masses act rigidly and apply force from the moment of contact but the less rigidly attached soft tissues have additional travel in their elastic attachments and their influence comes on later in the force profile, usually as a secondary increase in force after the main peak. Applying this to the kicking leg for the robot, it would be designed at 1.89 kg to represent just the bony mass of a 50\textsuperscript{th} percentile male, with the possibility of rigidly attaching a further 0.56 kg would then represent the bony mass of a 95\textsuperscript{th} percentile male. The equivalent mass of the soft tissues, 10.5 kg for a 50\textsuperscript{th} percentile and 13.65 kg for a 95\textsuperscript{th} percentile male, would then be attached in such a way so as to mimic the elasticity of their attachment in the human body. This would allow the kicking leg to act in a similar way to the human leg and create a similar force profile.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>50th Percentile</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>77</td>
<td>100</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.78</td>
<td>1.88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Segment Lengths</th>
<th>50th Percentile</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td>0.44</td>
<td>0.46</td>
</tr>
<tr>
<td>Shank</td>
<td>0.44</td>
<td>0.46</td>
</tr>
<tr>
<td>Foot</td>
<td>0.27</td>
<td>0.29</td>
</tr>
<tr>
<td>Total</td>
<td>1.15m</td>
<td>1.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Segment Masses</th>
<th>Bone Only</th>
<th>All Tissues</th>
<th>Bone Only</th>
<th>All Tissues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thigh</td>
<td>1.17</td>
<td>7.7</td>
<td>1.52</td>
<td>10</td>
</tr>
<tr>
<td>Shank</td>
<td>0.55</td>
<td>3.58</td>
<td>0.71</td>
<td>4.65</td>
</tr>
<tr>
<td>Foot</td>
<td>0.17</td>
<td>1.12</td>
<td>0.22</td>
<td>1.45</td>
</tr>
<tr>
<td>Total</td>
<td>1.89</td>
<td>12.40</td>
<td>2.45</td>
<td>16.1</td>
</tr>
</tbody>
</table>

*Table 7.3 – Table of anthropometric data used for designing the kicking leg*

Using equation 7.2 (Brach, 1991) below, values for the mass moment of inertia, J, of a 50\textsuperscript{th} and 95\textsuperscript{th} percentile human leg were made by assuming segment mass, m, acted at the centre of each segment. The distance from the pivot point, the hip, to the segment mass centre is given by l, which gives:
Using the equation along with data from table 7.3, we can calculate the mass moment inertia to be 3.06 kgm\(^2\) for a 50\(^{th}\) percentile male human leg and up to 4.39 kgm\(^2\) for a 95\(^{th}\) percentile leg.

### 7.4.3 Motor Specification

From the initial values of moment of inertia and foot velocity, the motor for the kicking leg was specified. The rigid kicking leg must accelerate up to the required velocity within \(270^0\), figure 7.8, as this represents the longest arc that will be available before impact. In a worst-case scenario this may become as little as \(90^0\). The motor will be used to drive the leg up until a point just before it contacts the anvil, at this point the motor will be disengaged and leg allowed to freely spin into impact. A freely spinning leg into impact gives a known impact condition whereas driving the leg through impact will produce more unknowns.

![Figure 7.8 – Plan view showing limitation on the rotation of the kicking leg](image)

The original specification requirements for the motor are detailed below, table 7.4. Fulfillment of this specification would mean a leg with a higher moment of inertia than a 95\(^{th}\) percentile man can still be spun up and impact at 20 m/s a value higher than has been measured in laboratory tests. These values are over-specified to ensure capability of the robot in use and maintain safe operable limits on the motor, but also allows scope for development in the future.
### Maximum Requirements of the Robot Kicking Motor

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leg Length</td>
<td>0.95 m</td>
</tr>
<tr>
<td>Leg Inertia</td>
<td>6 kgm²</td>
</tr>
<tr>
<td>Linear Velocity</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Range of Motion</td>
<td>270°</td>
</tr>
<tr>
<td>Contact Conditions</td>
<td>Freely rotating</td>
</tr>
</tbody>
</table>

*Table 7.4 – Table of the requirements on the motor for the mechanical simulator*

Lenze are the company who provided the motor for Holmes’ mechanical simulator, so were consulted for this project. The drive system they recommended to fulfill the above specification was a Lenze 9.2 kW and 336 Nm geared servo motor with resolver feedback, depicted in figure 7.9. This motor has the capability to rotate a rigid leg with an inertia of 6 kgm², from static to a maximum rotational velocity of 254 rpm within 270°. This equates to a maximum impact velocity of 25.27 m/s.

![Lenze 9.2 kW and 336 Nm geared servo motor with resolver feedback](image)

*Figure 7.9 – Picture of the Lenze 9.2 kW and 336 Nm geared servo motor with resolver feedback (Lenze, 2010)*

Due to the nature of the impacts to be carried out, Lenze also specified that a torque limiter should be fitted to the system. The limiter is fitted between the motor and the leg and if the torque applied reaches a certain pre-determined level, where damage can be caused to the motor, the torque limiter will disengage and cause the motor and leg to spin independently. The specified DSS torque limiter, size 4.160, is required as an
additional safety feature to prevent failure of the kicking leg due to high torques on the motor in the event of an error that causes the leg to be driven through the contact.

The motor supplied by Lenze includes a control box, which houses the control system for the motor that is also programmed by Lenze. The control system can monitor the kicking leg and record its position and speed every millisecond throughout an impact and store these in an ascii file, which can then be exported via a USB socket after each impact. The customised software allows the speed of the impact to be altered at the control box and the position of impact to be selected. A proximity sensor mounted on the frame will act as a “home” position for the kicking leg to allow calibration of the leg position before each impact. The default setting for the control system is to accelerate the leg up to the desired velocity and then to disengage the motor 5° before the impact position. This allows the kicking leg to be freely rotating as it impacts the anvil as was desired.

In addition to the ability to let the kicking leg freely spin into the impact, the control system of this particular motor comes equipped with the capability of reacting to feedback and adjusting the drive provided automatically. A force profile derived from a human on human impact could be input so the motor will continue to drive the kicking leg through the impact, the motor would then adjust its speed and torque to recreate the same profile. The feedback system between the motor and the leg will update every millisecond although whether this will be sufficient to replicate any force profile is unknown.

7.4.4 The Impact Force

Within the development of a representative testing procedure for cricket leg guards presented in Chapters 3 – 6, no previous work had been carried out investigating the transmitted force values on a players’ leg during a cricket ball on pad impact, so the test was developed by simply matching the impactor mass and velocity. The impact of a human leg on another human introduces far more complexity, there is “give” in the joints of the kicking leg and deformations of soft tissues that can occur in the struck opponent. Some work presenting the contact forces of a human on human impact was reported by Tsui (2011). This information will be useful during the design process and may allow a more representative kick to be developed.
Figure 7.10 – Graph showing the force-time profile of a front leg and rear leg roundhouse kick (Tsui, 2011)

In preliminary experiments carried out by Tsui, several values relating to the force profile have been identified. Martial arts practitioners were required to kick a Tekscan pressure measurement system attached to the outside of a taekwondo hogu, this hogu was worn by a volunteer who was still and braced during impact. Peak force values, impulse times and approximate force traces were taken. As shown previously by Tsui (section 7.2), the repeatability of these kicks was poor but by examination an average impulse time was taken to be 40 ms, and peak force was taken to be approximately 4 kN, figure 7.10.

The influence of the “give” in a human leg is apparent from this graph, the rigid bone structures have caused an initial steep rise in force, this peak is achieved in less than 5 ms. The traces then take a relatively long time to return to zero, this can be attributed to the leg itself still driving through the impact but the give of the joints delaying its influence and also the effect discussed by Pain and Challis (2006) of the soft tissues having a delayed response in loading because of their elastic attachments. What can also be seen in this figure is the limitation of the Tekscan system at measuring impacts, a low sampling frequency that can easily miss details of a short impulse, these limitations are also discussed in section 1.4.
This work provides a good first approximation of the force and contact time that would be encountered during a match, a 4 kN impact force with an impulse time of 40 ms. The term impulse time has been used here to distinguish between this and the contact time described in the work on cricket. The contact time was defined as the time the two impacting objects are in contact with each other measured visually. The impulse time is the time that force is applied between the two objects, which can only be measured using force or pressure measurement devices. Under these definitions contact time would be longer than impulse time.

These profiles will be impossible to match through the use of a rigid kicking leg and rigid anvil without building compliance into the simulator. The use of Tekscan pressure measurement equipment is not ideal for finding impact force but does give the only indication available of the forces that are applied to the outer surface of the hogu in this situation. This experiment represents the most relevant work in this area to date and the only indication of peak force and contact time of a game situation impact available despite its limitations.

7.4.5 Kicking Leg design

Initially the leg design was to be based on the same kicking leg used for the football kicking simulator. Holmes (2008) identified the dual plate design as the best option for this purpose. This design uses the flat plates to provide the in-plane bending stiffness with several spacers along its length separating the plates and providing torsional stability. This design gives the best strength to weight ratio but the spacers allow an easy method of altering the rigid mass of the leg and manipulating the moment of inertia to simulate that of a leg.

Taking this initial leg design, the size and shape were adjusted to try and achieve the mass and moment of inertia values for a human leg. The mass and moment of inertia were evaluated using a Unigraphics NX 3D CAD package, and even by using Aerospace grade 7075-T6 aluminium, an extremely light and stiff material, the rigid leg could not be designed to be below 10 kg and still satisfy the safety factors. This meant that at least initially it would not be possible to simulate the progressive loading action of the soft tissues that are not rigidly attached to the bone, so that the influence of their mass does not start to be felt until the impact has already initiated. It may be possible to account for this effect through additional stiffness and damping elsewhere within the system.
The kicking leg design was manufactured using 12 mm sheets of aerospace grade 7075-T6 aluminium in order to achieve the correct weight distribution along its length. The taper and the size of the spacers were altered to approach that of a 50th percentile leg, see Figure 7.11. The mass distribution can be altered by replacing the spacers, allowing a 50th percentile leg to be converted to a 95th relatively easily. As the spacers are distributed down the leg they can just be unbolted and replaced with heavier ones in order to change the rigid mass and inertia. The final design of the kicking leg used in the testing had a mass of 10.06 kg with a mass moment of inertia of 3.4 kgm$^2$. The working drawing for the kicking leg, along with other parts of the kicking robot design can be found in Appendix B.

At this point it would be pertinent to define the effective mass of the leg. If the kicking leg were to be replaced by a theoretical weightless rod with a concentrated mass at its tip, the effective mass at the tip can be used to represent the full kicking leg in calculations. The effective mass can be calculated using equation (7.3) below.

\[
\frac{M_e}{l} = \frac{M}{l_{cm}}
\]  

(7.3)

Where $M_e$ is the effective mass, $M$ is the total leg mass, $l$ is the total leg length and $l_{cm}$ is the distance from pivot to the legs centre of mass. For this leg design the effective mass is calculated as 4.05 kg.
Although achieving the correct mass and inertia is important the primary concern should be whether the leg can withstand the repeated impacts. A stress analysis of the leg was carried out to calculate the weakest point within the leg and to define the safety factor at the maximum allowable peak force. The safety factor of the leg is given as:

\[
\text{Safety Factor} = \frac{\text{Fatigue Strength}}{\text{Applied Stress}} \quad (7.4)
\]

The fatigue strength is a property of the material, and is the parameter used in a structure that will undergo repeated loading. For the specified aerospace grade 7075-T6 aluminium, the fatigue strength is specified as 159 MPa. The applied stress is a product of the applied load and the structural design and is calculated using the equations and dimensions shown in figure 7.12.

\[
\sigma = \frac{M_y}{I} \quad (7.5)
\]

Where

\[
I = \frac{bd^3}{12} \quad (7.6)
\]

\[
M = Fl \quad (7.7)
\]

M – Moment (Nm)

F – Force (N)

I – area moment of Inertia (m^4)

l – distance up leg from impact position (m)

y – distance from centreline (m)

b – breadth of beam (m)

d – depth of beam (m)

Figure 7.12 – Diagrams showing the engineering parameters of the leg design
Using equations (7.5), (7.6) and (7.7), a series of manual calculations were carried out to find the weakest points in the structure. The weakest points were found to be where the spacers are attached, as the holes through the solid aluminium plate reduce the area moment of inertia at this cross-section significantly. The stress values were calculated at each spacer to find the weakest point in the leg for the target impact force of 4 kN (section 7.4.4). The highest stresses were found at the attachment point for the drive shaft, due to the large moment arm for the impact force. This point was then used to calculate the maximum peak force for kicking robot operation and an accompanying safety factor. By using equation (7.4) the safety factor at various operational loads can be calculated. At the target peak force value of 4 kN the safety factor of the system is 4, the machine can tolerate peak forces of up to 16 kN before the safety factor falls below 1 and operation is unsafe. In the final design this central axis point will actually be reinforced and clamped into position on the torque limiter, this will actually increase the amount of material and decrease the stress values at this point. Rather than increase the operable load, this will be kept constant and the factor of safety will be allowed to increase.

For safety reasons it would have been preferable to have the kicking leg counter balanced. This would involve having a counter-weight on the other side of the main drive shaft, engineered to have the same inertia as the leg itself. In the event of a dynamic shaft failure the leg would theoretically still be balanced and should continue to rotate in situ. This works by shifting the centre of mass of the leg towards the centre of rotation so that the reaction force of the drive shaft pulling the leg inwards when it rotates becomes effectively zero. Without a counterbalance the centripetal forces on the leg are much greater and on dynamic shaft failure these forces cause the leg to accelerate away from the kicking robot base at a high velocity. The counter balance was not included as it would double the work required of the motor to accelerate the leg up to the required speed, but it would also double the inertia of the leg going into the contact, making the impact energy greater than required. The safety aspect of the counter-balance has also been incorporated into the design using the torque limiter, which should disengage well before the event of a shaft or leg failure.

7.4.6 Frame design

The frame is designed to house the motor, elevate the kicking leg to a suitable height for experimentation and to provide a solid and stable base to allow safe operation of the robot. It is depicted in figure 7.13.
The enclosed motor and servo system provided by Lenze measures 250 mm x 300 mm x 800 mm, which governed the sizing of the internal cavity required within the frame. A mounting plate was fixed to the side of the frame to allow mounting of the motor. Given the dimensions of the motor, it was decided to allow clearance room of 1 m within the frame, giving an impact height of 1.2 m. The 450 mm x 450 mm x 1000 mm central frame was constructed out of 50 mm x 50 mm box section steel and had an overall footprint of 900 mm x 1000 mm (working drawing included in Appendix B). As the 10.06 kg leg accelerates up to 254 rpm the resultant centripetal force acting outwards at the top of the structure was resisted by the inclusion of additional struts to at the base of the main frame that serve to increase the stability by maximising its base area. To further increase the stability of the structure, it will be bolted to the floor when under operation. Initial test impacts were to be carried out on the BOB (figure 7.3), these are discussed further in section 8.2, the height of the kicking leg at 1.2m will allow all heights of the hogu to be impacted as the BOB has an adjustable height range of 500 mm.

### 7.4.7 End Effector Design

The end effector is the interface between the robotic kicking leg and the hogu being tested. For the mechanical simulator, the end effector will be mounted onto the end of the kicking leg and attempt to mimic the contact area of a foot impacting a hogu. Significant research into this area was carried out by Holmes (2008), when investigating a suitable end effector for kicking a football, Holmes finished design used a simple hemispherical solution. As a first solution this same hemispherical design was adapted as shown in...
figure 7.14. It has a simple hemispherical contact area with a 90 mm diameter, constructed entirely of nylon it has a mounting point that securely attaches between the two plates of the kicking leg with four bolts.

![Figure 7.14 – CAD image of end effector design](image)

7.5 Final Design

The final design of the mechanical kicking simulator is shown below in figure 7.15. This represents the only mechanical simulator in the world currently designed specifically to simulate a martial arts roundhouse kick. The Lenze 9.2 kW geared motor is housed in a steel frame constructed of 50mm x 50mm box section. The central box section has supporting struts extending out of it that will be bolted to the floor to stabilize the machine. The motor is capable of accelerating the 10.05 kg kicking leg to speeds in excess of 20 m/s in less than 270° of rotation. Lenze also provide the operating system for the motor. The control box houses the electronics and allows input of impact velocity. It also has a USB socket for download of positional data throughout the impact. A proximity sensor allows positional calibration of the kicking leg before each impact, and the torque limiter is included as a safety feature to disengage the kicking leg from the motor and avoid failure.

The settings for the operating system require the impact speed to be input in terms of rotational speed measured in degrees/second. Using simple circle geometry and knowing that the distance between the pivot and the impact point is 0.95 m, we can easily change between rotational speed and linear impact speed using equation 7.8.
Linear Impact speed (m/s) = \([\text{Rotational speed (degrees/s)} \times 2 \times \pi \times 0.95] / 360\) \( (7.8) \)

As the manufacture of a mechanical kicking simulator for measuring performance of PPE is an entirely new area the design may appear initially crude. Various design aspects were taken from the successful design of a mechanical kicking simulator for football/rugby performed by Holmes (2008) and other aspects were over specified to provide a large operational window. By taking this approach it was envisioned that any catastrophic failure would be avoided and enough flexibility had been built in that the representative impact could be approached whilst still allowing for further refinement as part of future work.

### 7.6 Conclusions

Having identified the need for a new method capable of testing martial arts PPE in a representative way, a mechanical simulator of a martial arts roundhouse kick was designed and developed in order to replicate the impact conditions of a human kicking. The initial concept involved designing an equivalent human mass leg and accelerating it to appropriate kicking velocities using an electric motor. The target force profile was identified as reaching a peak force of 4 kN in 5 ms with an overall impulse time of 40 ms.
A rigid kicking leg capable of withstanding the impact loads was designed, along with a frame to house the Lenze specified 9.2 kW geared motor. A nylon hemispherical end effector was designed to complete the only mechanical simulator designed to replicate a human roundhouse in the world today.
8. Acquiring Force Data from the Kicking Robot

In the previous section the process of designing and manufacturing a robotic kicking leg capable of carrying out repeatable simulated kicks was reported. This robotic kicker allows the conditions of a martial arts kick to be replicated in a laboratory environment and can be utilized to create a more representative test for martial arts PPE garments. For the purposes of testing specific items of PPE, it is also important that there is a measurable outcome. This section looks at ways in which to assess the protective performance of these garments by measuring the transmitted force when impacted by the kicking robot. It describes the design process of such a system and concludes with a calibration of the system in order to ascertain the degree of uncertainty inherent in measurements made using such a system.

8.1 Introduction

Having designed and built a robotic simulator capable of mimicking a roundhouse kick this immediately opens up many possibilities for testing and monitoring performance of martial arts PPE that may be subject to these impacts. Unfortunately, without a system capable of quantitatively measuring the effects of these impacts the range of testing is limited and the specific aim of producing a representative test for measuring and comparing hogu performance is impossible.

Within this thesis, two main methods for acquiring force data from impacts have been investigated. The use of force transducers was investigated; these provide a consistent, easily set up force measurement method but have limitations in regard to mounting, the use of an anvil and vibrations caused by natural frequencies. The other method, presented in depth in Chapter 4 is the use of accelerometers on a freely suspended anvil. Again this method has its advantages and disadvantages for various applications.

The mechanical kicking simulator designed in Chapter 7 has position and speed monitoring of the kicking leg inbuilt into the control system. An alternative to developing an external method of measuring transmitted force may be to use this in-built monitoring system to approximate the deceleration of the kicking leg and calculate the forces from that.
The following chapter presents the work performed to develop an accurate and reliable system of measuring transmitted force through taekwondo hogu’s whilst used in conjunction with the mechanical kicking simulator producing the parameters determined by Tsui (2011) (figure 7.10) for a human roundhouse kick onto a human subject shown in table 8.1 below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Force</td>
<td>4 kN</td>
</tr>
<tr>
<td>Time to Peak Force</td>
<td>5 ms</td>
</tr>
<tr>
<td>Impulse Time</td>
<td>40 ms</td>
</tr>
</tbody>
</table>

Table 8.1 – Target parameters for a representative kick

8.2 Initial Test Impacts

Within the kicking robot motor drive system there is the capability to record the motor's position and velocity at 1 ms intervals. By analysing these data throughout all movements and during impact, it is possible to monitor the deceleration of the kicking leg through impact. Knowing its mass, it is then possible to estimate the forces during an impact utilising the principle of conservation of momentum. If this proved a successful method of measuring the force values then it would save considerable design work to develop a customised system.

The anvil for this work was the BOB, this is the same martial arts training device used in research measuring the force trace of a human kick (Tsui, 2011) (figure 7.3). BOB is a freestanding mannequin that is used for martial arts training. It has a water-filled base to provide support and keep it upright and is adjustable in height. Although stable, under larger impact forces it is liable to slip backwards and/or rock on its base thus not providing a consistent resistance throughout higher force and duration impacts, it should also be noted that in later work Tsui supported BOB against a wall to give higher repeatability.

The purpose of this method of testing is to establish whether there is a need to include additional instrumentation to measure the force or if the embedded data acquisition system within the motor controller is capable of recording reliable data for comparing the performance of several garments.
8.2.1 Method

Using the mechanical kicking simulator designed in Chapter 7, simulated kicks were carried out at multiple angular velocities, starting at 200 deg/s (3.32 m/s) and increasing at 100 deg/s (1.66 m/s) intervals up to 600 deg/s (9.95 m/s). These 5 individual impacts were carried out in order to assess a range of the forces that can be generated and to evaluate the feasibility of using the robots in-built feedback system to measure the force values.

An example of the raw data collected from the mechanical kicking simulator during an impact at 200 deg/s (3.32 m/s) is shown below in figure 8.1. The blue line indicates the data regarding speed of the leg and the green line is the position, numerical values for both plots are represented by the y-axis. Analysing the position data, it can be seen that the leg moves from a zero position until it impacts the anvil at 270°. At that point the slope of the line reverses direction as the kicking leg rebounds back.

![Figure 8.1 - Speed and position data for a 200 deg/s kick on BOB](image)

The speed data can be seen to be noisy which is inherent in the system. It can be seen that the leg accelerates up to a speed of 200 deg/s (3.32 m/s), which it maintains until impact. At initial contact, rapid deceleration is indicated by the steep slope downwards until final contact where the leg and anvil separate.
and the leg now has a negative velocity. The second drop at around 0.88 s indicates where the robot “catches” the leg again, i.e. the leg is no longer free spinning, to begin its return to the start point.

From the speed trace the beginning and end of impact can be seen and this can be used to give the impulse time of the impact. Initial contact is identified by the sudden drop in speed data, combined with the plateau and then slow downward slope of the position data. Final contact is identified as the position where velocity is at its minimum. From this graph values can be taken for the inbound and outbound velocities of the arm, using this information along with the known effective mass of the arm, the conservation of momentum equation (8.1) (Brach, 1991) shown below can be used to find the average force:

\[ \text{Impulse} = \text{Change in Momentum} \]

\[ \bar{F} t = m(v - u) \]  
\[ (8.1) \]

\[ F = \frac{m(v - u)}{t} \]  
\[ (8.2) \]

Where \( \bar{F} \) gives the average force over the impulse time, \( t \) is the impulse time, \( m \) is the mass of the impactor and \( u \) and \( v \) are the velocities pre and post impact respectively. Due to the rigid body style impact with relatively small deformations then assuming a symmetrical response through impact may provide a close approximation. By assuming a symmetrical response with minimal hysteresis, a sinusoidal distribution can be applied to drive an estimated force profile, as shown in figure 8.2. This shows an example of a derived force profile that can be produced using this method, from this an estimation of peak transmitted force can be made.
Figure 8.2 – Graph of predicted force against time for a 300 deg/s kick

This process was carried out for impacts carried out at 200 deg/s (3.32 m/s), 300 deg/s (4.97 m/s), 400 deg/s (6.63 m/s), 500 deg/s (8.29 m/s) and 600 deg/s (9.95 m/s) to give force readings. The impulse time was also noted for each.

8.2.2 Results

The results of the experiment investigating the effect of changing the kicking velocity on peak forces and impulse times when kicking BOB are discussed in the following section. Although a thorough error analysis has not been carried out, marker size is not used to indicate the uncertainty for reasons discussed further in section 8.2.3.
Three variables were monitored and those were the impulse time, the peak force and the rotational leg speed of the kicking robot. Figure 8.3 shows the variation of the estimated peak force values with the rotational speed of the kicking leg. The trend begins by having increased peak forces as the leg speed increases. The impact at 600 deg/s (9.95 m/s) however, the peak force was found to decrease. If we consider figure 8.4 as well, the contact times initially decrease with kick speed as would be expected, but they then begin to increase again around kicks of 500 deg/s (8.29 m/s) and higher.
Considering these two graphs together we can explain the initial slopes of the graphs; as the leg is swung faster, it has more energy so requires more force to slow it down causing higher peak forces to be monitored. The faster the leg moves, the shorter the period of time it is in contact with BOB so the lower the impulse times.

The reason both graphs reverse their initial slopes past a certain speed of kick is due to one of the main problems of using BOB to measure force. As it is free-standing it is possible for the boundary conditions to change and cause unexpected results like those shown here. For the kicks up to 400 deg/s (6.63 m/s), BOB remained in place with little movement being caused by the impulses, but as the impacts got higher in intensity it rocked further and actually slipped backwards on the floor. This slipping whilst in contact with the kicking leg is what causes the contact times to begin to increase again and the movement of BOB away from the leg is what causes the peak forces to drop. This is one of the main reasons why this method would be unsuitable for an accurate and reliable force measurement system. This variation in bounding conditions affecting the results is why Tsui resorted to supporting BOB against a wall in his work, in order to avoid this effect.
8.2.3 Discussion

Although it has been shown that the kicking robot speed data can be used to estimate the force profiles, there are two main problems. Firstly in testing a hogu’s performance the measurement taken relates to the force input into the hogu, not that transmitted through. Secondly, the assumption that the force profile is a half sine is a broad simplification and could also lead to errors in the results as well as preventing a deeper understanding of different possible hogu constructions altering the force profiles as they deal with the impacts in different ways. Both these factors lead to large levels of uncertainty in the experiment which cannot be accurately estimated.

Securing BOB to the floor to prevent slipping would help consistency, but it would be difficult to instrument. Given that it is not a rigid construction and may be liable to degradation under multiple impacts, this would cause error in this piece of testing and so should be avoided. This study has confirmed the need for a purpose built system for measuring the force transmitted through a taekwondo hogu; an instrumented system for measuring the transmitted force accurately and reliably, which produces repeatable boundary conditions and will work well in conjunction with the kicking robot.

8.3 Initial Force Acquisition System Designs

Having discussed the many flaws associated with using the in-built position monitoring in conjunction with BOB for measuring transmitted force, it was decided a custom force acquisition system needed to be designed. The proposed system needs to be capable of recording force measurements, provide repeatable boundary conditions and operate in conjunction with the kicking robot. The following section looks at four proposed design solutions that satisfy these criteria and evaluates which option should be taken forward to manufacture.

The first option considered was a force transducer based force measurement system. An extensive discussion of this is carried out in Chapter 3, though the major drawback of the excessively noisy signals induced by short duration impacts on an anvil remain. A very robust frame would be required to ensure rigidity of the mounting fixtures.
A similar bungee system to the cricket rig, Chapter 4, was considered, again utilising accelerometers to measure the force. The added difficulty in using this system comes from the requirement to keep the anvil very much heavier than the impacting object. The effective mass of the kicking leg is 4.05 kg, so the anvil would need to be considerably heavier to ensure that the leg returns in the direction it came after impact. A lower limit for this would be to ensure that the anvil is twice the mass of the impactor, but for optimal impact a value of up to ten times would be more desirable. Suspending this mass via bungees would require high stiffness’s and a heavy duty frame to support the system. Another issue would be the much longer contact times expected of the kicking impacts. Higher contact times require the anvil to move whilst in contact with the kicking leg for a greater distance. This in itself would cause two distinct problems. At greater displacements the effect of the bungees would influence the force measurements and would need to be considered, and if greater displacements were to occur, interference between the support cage and kicking leg could become an issue if not designed around.

A proposed way to simplify the bungee system was to hang the heavy anvil. This would remove several degrees of freedom from the system but would still give an accurate measurement in the direction of impact. Hanging the anvil does away with the need of high stiffness bungees but still has the problem that at high displacements the force vector from the straps used to suspend it would influence the measured forces and would need to be taken into account. This system would still need a heavy anvil to ensure separation after impact and a possible danger may be that at high displacements the anvil forces may become directed downwards onto the kicking leg, the leg is not designed to handle these forces and may become trapped and even damaged as a result.

An alternative to supporting the anvil from above is to support the anvil from underneath using a tower on a point pivot. This system has benefits but as with each of the others mentioned, some drawbacks. Again, this method of suspending the anvil will remove several of the degrees of freedom meaning it is not entirely freely suspended and not all the force applied can be measured. Another issue may come from the tower having to be rigid to support the anvil; as soon as rigid structures are introduced then vibrations need to be taken into account and it is possible some vibrations may be generated within a tower structure like this. Benefits of this system include not requiring such a large anvil as the others, as gravity will help to cause separation after impact, this will also avoid some of the problems mentioned about the hanging system catching and damaging the kicking leg. This falling away of the anvil would also allow longer contact times to be achieved.
The structure of this design will be more compact than designing an entire freestanding suspension frame and it may also be argued that the falling away of the tower may simulate a human withdrawing himself from the point of impact.

In order to decide which of these options to go with, a decision matrix was used. Three criteria were identified, accuracy of system, reliability of the system and the ability to manufacture, and the same system was applied as presented in section 7.3. The results are shown below in table 8.2:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Rating</th>
<th>Score</th>
<th>Rating</th>
<th>Score</th>
<th>Rating</th>
<th>Score</th>
<th>Rating</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Transducer</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Manufacture</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>11</td>
<td>7</td>
<td>12</td>
<td>6</td>
<td>10</td>
<td>7</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Rank</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.2 – Decision matrix of concept for force acquisition system design

Comparing the final scores it can be seen that the accelerometer based force measurement system in conjunction with a tower to support the anvil would be the most appropriate design based on the weighted design criteria. It should be noted throughout that the main design criteria are the accuracy reliability and ease of manufacture, but wherever possible flexibility will be built into the design to allow flexibility of use for expansion into further experimentation in the future.

8.4 Design of a Force Acquisition System

The following section describes how the initial design was developed into the final design and manufacture of a torso-shaped accelerometer instrumented anvil supported by a rigid tower free to rotate and fall about a pivot with a supporting frame and a catching system to reduce shock when arresting the tower. Figure 8.5 shows an initial design exhibiting all of the main requirements of the system. The anvil is supported by the
rigid tower, the tower was mounted on a thrust bearing to give full freedom to rotate under impact and a universal joint to allow it to fall in which ever direction the impact dictates.

8.4.1 Anvil Design

The first stage was to set the size and shape of the anvil. The purpose of the anvil was to give a mounting point for the hogus of a similar size and shape to a human torso. The anvil must be rigid to allow solid body acceleration on impact, this allows the accelerometers to monitor the movement at the centre of mass effectively and thus give an accurate measurement of the force. From anthropometric data (Peebles, 1998) the dimensions of a 50th percentile male chest were taken as 340 mm wide and 270 mm deep. These dimensions were applied to a rectangular cross sections of nylon 150 mm high and a radius applied to the edges. The resulting anvil is shown in figure 8.6.
This simplified shape was taken rather than the actual cross section of a human to give smoother surfaces for impact. This anvil manufactured out of nylon weighs approximately 13.5 kg. Similar to the cricket anvil, the three positions for mounting accelerometers feature cut-outs so that when mounted they are sunk into the anvil and protected from damage, these are also shown on the diagram, two on the rear, equidistant from the centreline and one on the centreline of the side section.

**8.4.2 Thrust Bearing and Universal Joint**

At the bottom of the tower an SKF 51110 50 mm inner diameter thrust bearing was used in conjunction with a Lenze carbon steel 25 mm inner diameter roller universal joint to provide the pivot point. This combination allowed both rotation and a hinge about this point to give the least restricted movement possible through the remaining three degrees of freedom. A ball and socket joint was considered instead of the universal joint but had a much smaller range of motion, this may have caused issues during impacts with longer contact times. This mounting removes three degrees of freedom from the system so only 3 accelerometers are required on the anvil to measure all accelerations. It is assumed that the tower is simply supported at its base whilst free to rotate, but this will be confirmed during the calibration process.
In order to calculate the accelerations of the anvil, the equations presented in section 4.2 are used again. Due to the constraints introduced by the supporting tower, 3 degrees of freedom are removed and thus $a_4$, $a_5$ and $a_6$ are reduced to zero. The set of equations can now be simplified to:

\[
\begin{align*}
    a_x &= \frac{a_1 + a_2}{2} \quad (8.3) \\
    a_y &= a_3 \quad (8.4) \\
    r_z &= \frac{a_4 - a_2}{2} \quad (8.5)
\end{align*}
\]

Where accelerometers 1 and 2 are mounted on the front face of the anvil and accelerometer 3 is the one mounted on the side. These equations are used to calculate the instantaneous accelerations at contact and thus find the forces acting on the anvil.

8.4.3 Tower Design

![Figure 8.7 – CAD image of the tower design for the force acquisition system](image-url)
The tower of the force acquisition system performs the important role of supporting the anvil at the correct height. A light and slender design so as to concentrate all of the mass in the anvil would be desirable, but the problem then becomes that it is a slender rod being struck at the end, which will introduce vibrations similar to those discussed in section 4.2. This kind of design would also be susceptible to damage both during impact and when caught by the frame. Figure 8.7 above shows the design used. A stronger and sturdier frame could have been designed but this would continue to add mass to an already heavy structure and increase the effective mass of the tower and anvil system further.

8.4.4 Catching System

Another important aspect of this system is the gas springs used to catch the falling tower. They are incorporated so as to dampen the impact of the tower as it falls and is caught by the supporting frame. Gas springs feature a spring in a sealed pressurized tube, the spring itself provides stiffness, and the gas gives further stiffness and some damping. They reduce the impact force of the falling tower being caught by the catching frame, which could damage both the frame and also the tower itself. The system designed uses two gas springs run parallel with a catching bar between them. Figure 8.8 shows the catching system under construction with two steel brackets to keep them running parallel and the bar at the bottom used to mount them onto the catching frame. The gas springs were designed so as to not bottom out under a “worst case scenario” impact. The springs require the forces to be directed along their length to function correctly, as the tower is falling on an arc, the angle of force application would change depending on the compression of the springs. This system was therefore designed so that at half compression of the gas springs the force would be applied directly down their length. Calculations using simple circle geometry show that at first contact and full compression the force vector is only off axis by a few degrees and should allow full function of the system through the entire range.
RS Camloc 202-2557-V/40 gas springs were specified, the pressure is adjustable, so once mounted the air pressure was adjusted to an appropriate level to soften a rapidly falling towers impact with the frame. In addition to the gas-spring catching system, the square tower was encased in a circular piece of nylon at the level it makes contact with the catching frame. This was to give a smooth surface to make contact with the frame and prevent damage being caused every time the towers falls.

8.4.5 Frame Design and Contact Considerations

It was important that should the target contact time of 40 ms be reached that the catching frame allowed enough travel for the distance that the tower would move during this time. In order to calculate this a system of modelling the impacts was derived.
Combining the mass of the tower with the mass of the anvil and the position of their centres of gravity, an effective mass for tower and anvil system was found using equation (7.3), this was 26.1 kg at the point of impact midway up the torso anvil. The effective mass of the kicking leg at the centre of the indentor is 4.05 kg as calculated in section 7.4.5. By modelling the system as an impact between two free bodies, a simplified model for the impact can then be derived as shown in figure 8.9. Here \( m_1 \) and \( x_1 \) are the effective mass of the anvil and tower combined and its displacement, \( m_2 \) and \( x_2 \) are the mass and displacement of the kicking leg, and \( k_p \) and \( c_p \) are the stiffness and damping of the PPE being tested, discussed further in section 1.7. From this model the following system of equations can be derived (Brach, 1991):

\[
\begin{align*}
    m_1\ddot{x}_1 + c_p\dot{x}_1 - c_p\dot{x}_2 + k_p x_1 - k_p x_2 &= 0 \\
    m_2\ddot{x}_2 - c_p\dot{x}_1 + c_p\dot{x}_2 - k_p x_1 + k_p x_2 &= 0 
\end{align*}
\]

A Matlab code was used to solve these equations at discrete time intervals \( \Delta t \) apart using the central difference method (a copy is included in Appendix A). The code uses the equations above to calculate the time history of the force encountered during impact using the input of the masses, damping coefficients, stiffness, initial displacements and initial velocities. Each factor could then be varied to tune the impact as close to the benchmark values as possible.

Using this code a series of reasonable stiffness and damping values were examined in combination with the known masses and a range of impact velocities to approximate the required contact time and force values and get a value for the maximum that will be required for the anvil during testing. It was found that under
most impact conditions a maximum of only 50 mm of travel would be required as a first approximation. In
order to build in flexibility and the possibility of future testing requiring more travel, a separation of 300 mm
between the tower and the catching system was designed in.

Both the swinging of the kicking leg and the falling of the tower system occur around pivots, and thus form
intersecting circular arc paths in different planes through contact with each other. In a linear impact, the
contact point between impactor and anvil remains constant throughout contact but for this impact with two
restrained arc movement patterns there will be a “slip” both vertically and horizontally between the contact
points of the impactor and anvil if they remain in contact with each other for anything longer than an
infinitesimally short period of time. The result of this would be non-central loading of the anvil, which could
affect the acceleration of the centre of mass and thus the force readings. In order to calculate the effect of
this, the maximum possible travel distance for contact of the two objects was regarded.

![Diagram](image)

*Figure 8.10 – The intersecting arcs of the kicking leg and force acquisition system tower*

The paths of the two arcs were considered independently using simple circle geometry for this scenario to
find the amount of “slip” to occur, figure 8.10. In a situation where there is 300 mm of travel whilst the two
objects are in contact a total of 46 mm of “slip” will occur sideways due to the arc of the kicking arm and only
30 mm of slip vertically due to the movement of the tower. Also, at 300 mm the retarding force applied by the
inclined tower becomes a consideration and may affect the accuracy of the results. These are undesirable conditions but for 300 mm of travel to occur whilst in contact there would need to be a large amount of compliance and deformation within the tested garment. For the dimensions and mechanical properties of most martial arts PPE it was predicted that travel would be less than 50 mm, which correlates with less than a total of 10 mm of total “slip”, if significant deflection is measured in the final testing, the effect on force readings may need to be considered.

The frame of the force acquisition system was constructed from the same 50 mm x 50 mm box section steel as that used for the kicking robot. Its purpose is to catch the falling tower post-impact, but allow enough room for the tower to be impacted and travel unimpeded. The box section extending out from the frame allows it to be attached to the kicking robot to maintain the correct spacing and also to prevent excessive movements, these features can be seen in figure 8.11.

8.4.6 Final Force Acquisition System

A final consideration during design of this structure was to accommodate flexibility in the positioning of the tower in relation to the kicking robot. The reasons for this were two-fold; firstly, if the torso anvil were rotated so as to measure impacts to the side of the anvil, the point of contact with kicking robot leg is no longer normal to the anvil, being able to reposition the tower would allow normal impacts to the side of the anvil whilst still maintaining a normal impact at point of first contact.

Secondly, building in this flexibility would also allow design of further anvils for testing of various other pieces of martial art PPE under these conditions, different sized anvils again would need this re-positioning feature to allow a normal impact at an optimal contact point for the catching system to be useful. This flexibility was achieved by mounting the entire initial design on another base frame. This base frame was directly attached to the kicking robot and has 9 different mounting points at 50 mm intervals allowing the force acquisition system position to be varied by up to 400 mm. The final designed force acquisition system is shown below in figure 8.11.
This system represents a unique piece of work designed to work in conjunction with the novel mechanical kicking simulator designed in Chapter 7. The primary aims were to design a system capable of measuring the transmitted forces accurately and reliably, whilst being feasible to construct within the required timescale. In addition, it is foreseen that this piece of equipment will be used in the future so flexibility has been built into the system to allow for modifications.

8.5 Calibration of Force Acquisition System

In order to assess the validity of the newly designed system a series of calibration tests were carried out. The purpose of this calibration was to compare the forces imparted on the anvil with those measured by the force acquisition system.

The calibration was carried out by tapping a small hole into the front of the anvil itself in the centre of one of the flat faces at the point where the kicking leg would contact the anvil. The same Brüel & Kjær 8230-003 force transducer used on the force hammer in section 4.4 was then mounted in this position and used to
directly measure the force imparted onto the anvil. The anvil was instrumented with three of the 4375_V Bruel & Kjaer accelerometers running through the same charge conditioning amplifiers as detailed in section 4.3. National Instruments Data acquisition hardware (National Instruments, 2011) running M+P international SO analyzer was used to capture data from both accelerometers and force transducer. The data were then exported to Matlab where the force signal from the force transducer was compared to that calculated from the accelerometer readings.

Initially impacts were carried out at the minimum speed of 65 deg/s (1.08 m/s). As suspected this generated short contact times, which instead of creating a clean measurable force trace, excited the anvil/tower system to oscillate causing the force reading to beunreadable. By utilizing the PSD function in Matlab (Appendix A), the natural frequencies responsible for the oscillations could be identified.

![PSD Graph](image)

*Figure 8.12 – PSD of the tower/anvil system when struck by the nylon end effector*

An example of one of the resulting PSDs with the relevant frequencies highlighted is shown in figure 8.12 above, demonstrating the natural frequencies of the system that need to be avoided to generate a clean force profile. The highest frequency peak at 400 Hz represents a contact time of 2.5 ms, if contact times are sufficiently higher than this then some of these excessive vibrations will be avoided.
Running the same 65 deg/s (1.08 m/s) impact but mounting hogu 1 (which is described and tested in Chapter 9) on the anvil in front of the force transducer elongated the contact time sufficiently for a cleaner force trace to be extracted. An example of this is shown above in figure 8.13. The green line is the input force on the surface of the anvil from the force transducer, and the blue line is the force calculated from the measured acceleration of the anvil itself. Apart from the noise on the measured signal, the two traces follow a similar force profile throughout the duration of the impact, thus justifying the validity of the force acquisition system. There is still some vibration within the accelerometer based measurement system but this has been reduced by increasing the contact time of the impacts to those that would be found during the hogu testing. The force transducer trace is smooth and clean, which is expected when it is used to measure the point force applied like this.

Immediately post-impact, where the green trace falls back to zero, the measured blue trace does not. This is the point where the anvil is falling under gravity and so is still being acted upon by a force, the second large spike in the accelerometer force data is where the anvil is being caught on the spring dampers of the force transducer.
acquisition system. The catching force is acting in the opposite direction to the impact force, but both are shown as positive values due to only their magnitudes being used throughout the post-processing.

To complete the calibration, this impact was repeated five times and the results were analysed in Matlab. Peak force values were found for the force transducer (input force) and accelerometers (measured force) for each repeat. The difference between these two values were then found for each repeat. All measured readings were higher, with a maximum difference of 17% and a lowest difference of 7%.

The reason this force transducer is not used to measure the transmitted force during the final testing is that in this case the force gets applied at a single focused point, rather than with the more generalised contact of the end effector that is more representative of a human foot. This setup worked for calibrating the force transmitted but in order to use it in the form of a representative test to measure the total force transmitted to the torso, and anvil would need to be fitted to the front of the force transducer, lowering its natural frequency and introducing the type of vibrations seen in Chapter 3.

8.6 Conclusions

Within this chapter the need for a reliable accurate system for acquiring quantitative force data from impacts with the kicking robot was clearly identified. The methodology of estimating the peak forces using the BOB was found not to be sufficiently accurate or reliable enough for the series of comparative tests required of it. Subsequently, a novel system was developed to facilitate collection of impact data. This system incorporated a torso sized anvil utilizing a similar accelerometer based system of force measurement as that introduced in Chapter 4. Mounting the anvil on a pivot removed three degrees of freedom from the system thus requiring fewer accelerometers but did introduce some vibration. Calibration of the system showed its efficacy and comparison of the data generated by the new system with a force transducer showed a maximum discrepancy of 17% at peak force.
9. Robotic Kicking Tests on Taekwondo Hogus

Utilising the custom designed kicking robot and integrated force acquisition system, it is the aim of this chapter to report the parameters that were found to best represent a taekwondo kick. These parameters were used to drive a representative test for taekwondo, comparing a series of nine commercially available hogus using various performance metrics. An analysis of the materials and structure of the pads is included to allow discussion of the hogus impact performance and how this relates to their construction.

9.1 Introduction

Within the WTF rules, no requirements are given as to the level of protection required of the hogu, these are set out separately. The British Standard (BS EN 13277-1:2000 & BS EN 13277-3:2000) sets out a series of requirements and testing protocols for the hogus. Figure 9.1 below shows the required areas of protection, each of the measurements is set relative to the competitor’s height. This defines the areas of protection for the hogu, it should be noted that this only covers the main body area; the shoulder protection is not currently specified although recommendations for changing this have been made. (Private communication, William Darlington, 2006).

![Figure 9.1 – The areas of protection as designated by BS EN 13277-3:2000](image)

To test the protection level, the standard requires that the hogu is placed on a flat plate with a force transducer inset, it is then held in place by a 10 kg, 140 mm diameter compression ring. The impact test takes place in the centre of this ring. An 80 mm diameter, 2.5 kg cylindrical striker with a curved contact
A minimum of 3 impact positions are selected and each is impacted with a 12 J impact. To avoid failure, all measured forces must be below 3 kN.

Although a single pass/fail criteria is specified across all areas of the pad in regards to transmitted forces, in work carried out by Webster (2010) fighters perceived that they required more protection on the side of their bodies than the central chest region or back. The shoulder regions and lower abdominal areas were perceived to require the lowest protection. This perception of needing different protection levels in different areas of the garment is something not encompassed within current testing regimens. It should be noted that the overall protection of the garment was only ranked fourth in order of priority of six themes of importance for the perception of the performance of the pad overall. These six themes in order were fit, weight, thermal comfort, protection, aesthetics and sensorial comfort.

Work by Tsui (2011) was carried out comparing the performance of taekwondo hogus from a biomechanical perspective, examining the effect of increasing biofidelity in the anvil and its effects on transmitted force values. This series of tests showed the variation in performance of the pads under differing boundary conditions, a result which has been mirrored elsewhere in the literature when comparing items of PPE under rigid anvil impacts to more biofidelic testing apparatus (Pain, 2008). It is the purpose of this chapter to measure the impact performance of the hogus under game specific impacts without compromising the exact nature of a material test by introducing more compliance through biofidelic anvils.

### 9.2 Analysis of Pad Structure

The internal structures of the body protectors to be tested were examined such that a subjective link might be drawn between the fighter’s perception of the hogus, their physical structure and the pads performance under representative testing. Nine items of PPE are to be tested: five ‘Standard’ hogus, two ‘Instrumented’ hogus, one ‘Custom’ hogu and one ‘Coach’ training pad body protector.

Work on the players’ perception of taekwondo hogus was carried out by Webster (2010); he used a series of interviews and questionnaires to develop a hierarchy of factors that determined the players’ perception of comfort for a particular hogu. Six general dimensions were identified in order of importance as fit, weight, thermal, protection, aesthetics and sensorial comfort. Here we are concerned mainly with the protection of
the pad, which was only ranked as 4th most important, but he also identified that several of these factors intertwine. The following sections evaluate the pads purely from a perception of protection standpoint, with the understanding that other factors, such as the feel of materials, can also have an influence.

9.2.1 Standard Hogus

Five commercially available hogus were selected, these represent a standard design which typically consisted of the outer covering, red on one side and blue on the other making them reversible and wearable by either competitor, two layers of a soft thin foam sandwiching a thick layer of stiffer foam which will provide the majority of the protection. The major variable is the thickness and grade of this central foam section and it is this variable that will affect the performance of the pad the most. The covering materials also change but this is more likely to affect a fighter’s perception of quality than the actual performance of the pad itself.

In order to compare the hogus, two variables were considered. The thickness of the inner foam was measured to give a quantitative measure of how much protective foam there was, in addition the relative density of the foams was compared by hand, and this gave enough information to categorize the density as high, medium or low when compared to the other hogus. These two variables can be compared for the five hogus to give a measure of perceived protection against which the experimental data can be compared, this data is displayed in table 9.1, and the accompanying images can be seen in figures 9.2 – 9.6.

<table>
<thead>
<tr>
<th>Hogu</th>
<th>Central foam thickness (mm)</th>
<th>Foam density</th>
<th>Perceived performance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (figure 9.2)</td>
<td>19</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>2 (figure 9.3)</td>
<td>15</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>3 (figure 9.4)</td>
<td>14</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>4 (figure 9.5)</td>
<td>17</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>5 (figure 9.6)</td>
<td>16</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Table 9.1 – Perceived performance of taekwondo hogus
Figure 9.2 – Photos showing the internal structure of hogu 1

Figure 9.3 – Photos showing the internal structure of hogu 2

Figure 9.4 – Photos showing the internal structure of hogu 3
9.2.2 Instrumented Hogus

Next, the two instrumented hogus are discussed. These are classified by the incorporation of systems that can detect impacts and automatically score a fight. Both achieve this goal in different ways but ultimately decipher whether an impact has scored or not and relay that information wirelessly back to a computer so that they may be used freely in competition.

Hogu 6 is the first of the instrumented hogus. It has the same manufacturer as hogu 1, so incorporates much of the same design but has some additional features to incorporate the automatic scoring system. The pad is instrumented with a rubber bladder across the scoring areas of the chest, sides and back. This bladder contains a series of inter-connected sealed channels which all lead to one exit hole in the top corner. From this hole leads a tube that connects to an electrical device housed in the shoulder, this device measures changes in air pressure within the channel. On impact to the scoring zones, the bladder will be compressed, changing the air pressure in the tubes leading to the air pressure measurement device, if this change is large
enough, then a score is registered and this is transmitted via Bluetooth to a laptop running the scoring software. An x-ray of the bladder is shown in figure 9.7 below, the x-ray allows the internal structure to be seen, to give scale a one pence piece was included on the first x-ray.

![X-rays showing the internal air bladder of hogu 6](image)

The pad has 17 mm of the same white foam as hogu 1 for its main source of protection, but in addition it has the 8 mm thick rubber bladder laying over it in the scoring zones, the blue areas in figure 9.8, and an additional 6 mm of white foam glued onto the areas covered by the white material on the exterior, top and bottom to ensure a smooth striking surface overall. This is then covered with the same thin foam and simulated leather outer covering as hogu 1. The major difference with this hogu is that due to the incorporation of the automatic scoring system, this pad is not reversible meaning separate hogus need to be purchased for a red and a blue competitor. Because this is no longer reversible a fabric that allows a flow of air under the garment is incorporated on the underside of the pad, designed to help players maintain a lower body temperature and as such contribute to player comfort. Having a thick layer of protective foam overlaid with a rubber bladder, which although not designed for the purpose will still provide some protection, this pad would be expected to the most protective. It should also be noted that it is the heaviest pad of those on test here that could be used in competition.
Hogu 7, figure 9.9, is the second of the instrumented hogus. This pad uses a combination of contact sensors in the scoring zones that detect contact from the specially designed boots and mitts, figure 9.10, which have conductive contact areas mounted on them. Pressure sensors are also incorporated in the designated scoring areas on the pad itself. The pressure sensors are shown inset into the black foam padding in figure 9.11. These measure the pressure of an impact and relay the information to a blue tooth device housed in the shoulder. If the measured pressure exceeds a pre-set threshold indicating a scoring impact, a blue tooth signal is sent to a laptop running the scoring software that keeps score and also times the bout.
The pressure pads are 14 mm thick and have a thin plastic sheet over them intended to distribute the forces. The pressure pads are layered on a 3 mm section of rigid black backing of high density foam, around the edges a border is created with 14 mm of a black protective foam. Similar to the other instrumented hogu, because of the nature of the detection system this pad is not reversible, allowing extra player comfort features to be included on the underside.

**9.2.3 Custom Hogu**

A custom hogu, known as hogu 8, was developed utilising the Confor viscoelastic polymer foam as a direct replacement for the EVA foam and rubber bladder sections of hogu 6, figure 9.12. Confor foams, also referred to as memory foams, are formulated to offer large degrees of hysteresis, which means they can
absorb large amounts of energy from an impact. Certain drawbacks in the application of Confor foam are known, such as the high levels of thermal insulation likely to cause problems with the athlete’s thermal regulation and comfort. The low bending stiffness of the material in its sheet form makes it well suited to such a body fitting application.

9.2.4 Protective Coaching Pad

Hogu 9 is not strictly a hogu, figure 9.13, but is used in martial arts training. Its thickness varies greatly over the different areas of the pad, but the multiple layers of foam padding can be clearly seen in figure 9.14. In general the pad has thick (approximately 20 mm) layers of soft foam at the front and back which sandwich a central protective core, 15 mm of stiff energy absorbent foam sits behind two 11 mm thick layers of white foam. This is just a general section; each of these thicknesses’ can vary greatly over the entire area. Due to its thick and inflexible nature the pad is shaped to the fit the user’s body and does not need to be reversible as it will never be used in a scoring competition.
This pad is commercially available, but is not for use by athletes whilst training, it is especially thick and bulky and makes little compensation for freedom of movement. A coach may wear it and take impacts from an athlete with even less fear of injury because of the extra protection afforded. This pad is included to provide a comparison of the amount of protection that can be provided by thicker layers of padding.

![Figure 9.14 – Photo showing the internal structure of hogu 9](image)

### 9.3 Matching a Human Kick

The robotic kicker and the force acquisition system so far have only been used together to calibrate the force acquisition system. Theoretically, it has been shown that the system as a whole would be able to recreate the conditions of a human on human impact closely enough to be representative for benchmark testing. The following section looks to manipulate certain available parameters in order to replicate a human kick as closely as possible.
The force profile recorded from a human on human round-house kick that defines the objective to be replicated is shown in figure 9.15 (Tsui 2011), this impact was carried out whilst the competitors wore hogu 1 and the details are discussed further in section 7.4.4. Ideally all features of the profile would be matched, but certain key features, such as peak force and loading rate are considered a priority as it is these characteristics that are most likely to lead to injury.

In order to investigate this, a small pilot study was conducted to attempt to match this force profile. The same hogu used by Tsui was attached to the force acquisition system, before being impacted at increasing speeds, ranging from 65 deg/s to 210 deg/s.

9.3.1 Method

The force acquisition system was setup and instrumented with the 3 accelerometers, run through the charge amplifiers and data acquisition software as detailed in section 8.5, in order to record the data. Hogu 1 was mounted on the anvil. Impacts were carried out on the hogu at 65 degs/s (1.08 m/s), 75 degs/s (1.24 m/s), 100 degs/s (1.66 m/s), 125 degs/s (2.07 m/s), 150 degs/s (2.49 m/s), 170 degs/s (2.82 m/s), 190 degs/s
(3.15 m/s) and 210 degs/s (3.48 m/s), before the peak forces went higher than required and testing was ceased. After every impact the results were recorded and the anvil reset into an upright position. The results were then exported to Matlab for post-processing where the transmitted force values were calculated from the accelerations as discussed in section 4.3.

### 9.3.2 Results

Variability in this section is indicated in the usual way, variation in peak force is shown as -17% as discussed in section 8.5, and contact time variability is given as 7% as discussed in section 3.6.2.

![Figure 9.16 – Graph of force against rotational speed for the mechanical simulator](image)

Figure 9.16 shows the peak force values for impacts from the mechanical simulator at various speeds. Generally there is an increase in measured peak force with increasing impact speed, the incremental increase in measured peak force increases for higher impact speeds.
Figure 9.17 shows the contact time values for impacts from the mechanical simulator at various speeds. Generally there is a decrease in the contact time as the speed of impact increases. If we compare the values measured here with the contact time of 45ms found by Tsui (2011) for human on human, shown in figure 9.15, then getting close to the contact time would require a slow impact of less than 100 deg/s (1.66 m/s). However, considering the peak force of around 4 kN would require impacts of around 200 deg/s (3.32 m/s). To make a decision on the most appropriate impact speed, the time to peak force (TTPF) needs to be considered.

9.3.3 Time to Peak Force

The TTPF is the time from the initial rise in the slope, caused by the impact, to the peak force value being reached. This value focuses on the initial slope of the curve, and by matching it along with the peak force value an accurate approximation of the damaging part of the taekwondo kick can be made. The TTPF value is calculated from the force trace, the point of initial contact is identified manually, then the time between this and reaching peak force is recorded.

If we consider the mechanisms of injury discussed in the literature review section 1.3, viscous injuries were discussed as being most dangerous in the chest, a result of rapid compression of the cavity, the high-risk
Impacts to the abdomen are ones which cause high deformation levels. Maximum rates of compression of
the chest and abdomen will only occur up to the point where peak force is reached. Both these mechanisms
for injury are influenced much more by the imparted force up to the peak and the time it takes to get there
rather than the overall length of the contact time, thus suggesting that a TTPF measurement may be more
pertinent in this situation.

In human on human kicking impacts, the extended length of the down slope of the force profile comes from
the previously discussed mechanisms; of the delayed influence of the mass of the soft tissues during an
impact (section 7.4.2) and the large amount of “give” within the system (section 7.4.4). Attempting to mimic
this part of the slope may improve biofidelity of the impact, but should not give any clearer indication to
establish protection against injury.

Variability of the TTPF values was established through work similar to that carried out for the video analysis
in section 3.6. An arbitrary force profile was selected from impacts of the kicking leg on hogus and the TTPF
value was measured once on nine consecutive days, for a total of nine results. Analysis of these results
showed that the maximum variation from the mean value was just 2%.

Figure 9.18 – Graph of time to peak force against rotational speed for the mechanical simulator
The TTPF values for each of the impacts were calculated and are plotted against rotational speed in figure 9.18, above 100 deg/s (1.66 m/s) there is the expected trend of increasing rotational speed leading to a decrease in the TTPF as the quicker impact velocities mean the hogu reaches full compression and the peak measured forces sooner. The result measured at 100 deg/s (1.66 m/s) could be considered an anomalous result compared to the relatively linear pattern observed from all the other results.

9.3.4 Discussion

By focusing on the TTPF and the peak force values measured in the human on human impacts of Tsui, these most important features of the force profile are matched closely. Figure 9.19 shows the force profile of the nylon end effector impact at 190 deg/s (3.15 m/s) & 210 deg/s (3.48 m/s) impacting the hogu attached to the force acquisition system, overlaid on the profile of the human on human kick data. Beyond the peak value the traces diverge but the initial slope and peak values match closely, and as already discussed, this is the area most likely to cause injury so is of most interest in terms of protection levels of the pads. This is the setup that will be used for the final testing of the taekwondo hogus impacting at 200 deg/s (3.32 m/s).
This 200 deg/s impact represents a linear impact velocity of only 3.32 m/s. This is much lower than the average 15 m/s impact velocity reported in the literature (section 7.4.1). This was a necessary compromise at this stage in order to match the peak force and shape of the force trace due to the high mass and rigidity of the kicking leg, and to keep the loading of the kicking leg within the designed safety parameters.

9.4 Method

In the British Standard (BS EN 13277-3:2000) testing protocols a minimum of three positions are tested. This gives the tester the ability to look at areas of particular vulnerability and test in these areas to see if protection levels are compromised. The purpose of the representative test presented here is not to pass or fail a certain hogu, but to look at the make-up of the pad and ascertain the level of protection this would afford compared to the others. As most pads are generally consistent in terms of construction, the position of this impact is not considered significant so all tests are conducted in the same position. It is possible that by testing in different positions, particularly on the sides where the pad is under increased tension around a curve that the protection levels may differ here, but that is beyond the scope of interest of this work.

![Figure 9.20 – Position of impact marked on hogu](image)

The approximate position of the point of impact is indicated in figure 9.20. This represents a position which would sit just over the sternum, a bony structure covered by little other soft tissues so may represent the position where if impacted on a human, force levels would be most intense.
Five impacts were carried out at this site for each of the tested hogus at a speed of 200 deg/s (3.32 m/s). Five repeats were carried out as this gave a better indication of both the consistency of the results and also the hogu’s deterioration under repeated impacts. This second point is pertinent in taekwondo given the amount of impacts that can be delivered in a match (Lee, 1983) and the speed with which they can be repeatedly delivered to the same area.

The variables that were monitored were the TTPF and the peak force value itself, a mean of the five values was taken and this was the reported value. Both TTPF and peak force were measured from the accelerometer readings taken throughout. The same setup of accelerometers, charge amplifier, and data acquisition system were used before the results were exported to Matlab for post-processing as discussed in 4.3. The method of deriving TTPF is discussed in section 9.3.3.

In turn, each of the hogus was attached to the torso shaped anvil, they were held in place by their own set of ties or Velcro fasteners. Their position was adjusted so that the end effector lined up with the chosen impact position and the series of five impacts was then carried out at 200 deg/s (3.32 m/s), with the results recorded and the equipment reset after each. The results are reported in the following section.

9.5 Results

In this section the results of the benchmark testing of the nine taekwondo hogus are reported. Initially the average values for TTPF and peak force are considered and the overall protection level of each of the pads is discussed along with any that may be considered inadequate. After this the trends seen in the pads across the series of five impacts is investigated and any trends pointed out. Analysis of the experimental results shows that the force measurements could be over estimated by up to 17% for the peak force values (section 8.5) and measurement variation is 2% for the TTPF (section 9.3.2), this is visualized in figure 9.21 with error bars, but omitted from 9.21 and 9.22 for clarity.
Figure 9.21 – Graph of peak force against time to peak force for the hogus

Figure 9.21 shows the average TTPF plotted against the average of the peak force values for each pad across the five impacts. A more protective pad would likely have a lower peak force value and a higher TTPF. Therefore the better performing pads appear in the lower right hand side of this graph with the least well performing, those with high peak forces reached in a short period of time thus least likely to protect against injury, in the top left. Expectedly hogu 9 has performed the best with its extra thick padding it has lowered the peak forces the most and greatly increased the time to reach this value. Hogu 4, 5, 6 and 8 have all reduced the peak forces down to between 2.5 kN - 3 kN but each with differing TTPF values so a comparison of players perception of the impacts on this measurable difference would be interesting. From the graph hogu 4 gave the best protection levels of the competition use hogus and hogu 3 gave the worst.
In general, figure 9.22 showing the peak force for each repeat of the testing for each hogu, demonstrates that there is a general increase in measured peak force with increasing number of impacts across all the pads, this increase ranges from 5% up to 50% for the different pads. Hogu 9 has the lowest measured force values by a significant margin, this is unsurprising given the number of layers of foam and overall thickness of the garment. This pad also experienced the lowest increase in peak force over the five impacts which will again be because of the thickness of the padding, this test is well within the capabilities of this pad so there is little if any damage being caused with each kick and thus subsequent impacts are not affected.

Above this there is a cluster of four hogus, 4, 5, 6 and 8, with very similar force values and slight increase across the repeats. These four could be categorised as having better than average performance. Hogu 2 sits 500 N to 1000 N higher again representing a slightly lower level of performance but perhaps surprisingly, with higher peak forces again is hogu 1, this being a widely used pad at international tournaments and also has one of the thickest layers of padding represents one of the worst performing pads. The performance of hogu 9 is different as the values fluctuate higher and lower with each impact, this pad has a different structure and as mentioned the pressure pads will be providing most of the force dissipation so it is possible that the materials in these may be causing this unusual response. Hogu 3 had a poor performance and the
experiment had to be stopped after three impacts so as not to risk damaging the testing equipment. Its initial peak force value was already relatively high, but its deterioration with repeats made continuing the testing unsafe.

![Graph of time to peak force for each impact on the hogus](image)

*Figure 9.23 - Graph of time to peak force for each impact on the hogus*

The difference between the performances of the majority of the hogus is much less discernable with regards their TTPF across all five repeats, as shown in figure 9.23. There is a general trend of decreasing TTPF across the five impacts caused by the unrecovered damage caused to the pad during a previous measurement leading to a subsequent more severe impact. Six of the pads start with TTPF in the 0.011 s - 0.014 s range and they remain closely performing throughout, after the fifth impact they still sit within the 0.0085 s - 0.012 s range. Even the poorly performing hogu 3 on its peak force measurements does not stand out as particularly poor on this variable, sitting just below this tight grouping.

### 9.6 Discussion

It is interesting to note the range of performances shown in section 9.5 for the hogus when all are found to pass the same British Standard test. It is possible, that particularly in the case of hogu 3, the materials used
are adequate for the lower mass, lower momentum impact of the British Standard, but when tested under circumstances more representative of a game situation they clearly seem to be inadequate compared to those used in the other pads. Another possibility is that this representative protocol is testing the hogus above and beyond the British Standards and that when tested under less intense impacts the noticeable differences in performance would be lessened. Either way, a test that is more representative of the in-game impacts has revealed differences in performance that may not be revealed by the British Standard test. The performance of hogu 3 does leave doubt in the experimenters minds as to whether its protection levels are adequate.

Hogu 3 also performed poorly in the tests reported by Tsui (2011) on rigid anvils yet performed better as the boundary conditions became more biofidelic. This was one of the thinner pads on test so would be capable of less direct force absorption, but it incorporated one of the stiffer foams which would give better load spreading capabilities, this reduces the pressure and the depth of penetration into the body rather than directly absorbing the impact energy. Thus poor performance on the test presented in this chapter but may not be inadequate depending on the primary injury mechanism.

The performance of the instrumented hogus and the custom hogus matched that of the standard hogus despite the vastly different constructions. The small variations in construction of the standard hogus did not lead to an accurate prediction of their varying performance level. The structural analysis leading to a perception of the afforded protection did not match up to the quantitative measures taken with the representative testing protocol. What structural analysis did allow, was an understanding of the mechanism when performance was different to what was expected.

Overall, hogu 9 might be considered the best performer with a distinctly higher TTPF across the five repeats, this combined with it’s low peak force values would indicate the far lower level of discomfort a wearer would encounter whilst receiving repeated blows in this garment, and the far lower likelihood of getting injured should a severe impact be delivered. Hogu 4 has a clearly higher TTPF than the majority of the other hogu’s and almost no deterioration in performance with repeated impacts. Taking this alongside its fairly low transmitted peak force values from the figure 9.22 it is clear that of the standard hogus this may be considered the best from a protective standpoint, but a clearer understanding of the mechanics involved in causing injury would be needed before firm conclusions can be drawn. When analysing the structure of the
pad there were no particular features which made it stand out as a superior design, this therefore highlights how important work of this nature can be.

9.7 Quantifying a Representative Test for Taekwondo

Within the development of this testing procedure a differing approach was taken from that used when developing the cricket representative test. Due to the much more complex nature of a human kicking another human, initially matching the impacting mass and velocity lead to an impact which was too far removed from the required game specific impact. The importance of matching the impact velocity and impact mass were downgraded in order to match the force profile more closely.

The kicking leg having already been designed to be as light as possible within the allowable safety factors could not be reduced in mass any further so the impact velocity had to be lowered. By doing so the variables of peak force and TTPF could be matched closely. These were decided to be the most important variables in regards being appropriate indicators of injury.

The work reported in this chapter represents a significant step towards producing a representative test for taekwondo, but significant refinement is required before it can be considered truly representative. This may include re-design of the kicking robot leg or incorporation of increased biofidelity within the testing equipment but this work is beyond the scope of this project. The testing protocol as it stands is still an improvement over other testing protocols currently available.

9.8 Conclusions

Although the entire force profile of a human on human kick could not be simulated exactly at this stage, by focusing on the peak force and time to peak force factors, the part of the impact expected to be highly associated with causing injury was matched. This was achieved for the mechanical simulator through a compromise on impact velocity, impacting at 3.32 m/s. Measuring the ability of the hogus to mitigate this impact is an indicator of their ability to protect against injury.

Examination of the hogus from an engineering perspective revealed small differences in their construction, but nothing truly distinct. The subsequent impact testing revealed large differences in performance over both
individual performances and deterioration with multiple impact, peak forces varied between 0.5 kN - 7.5 kN and TTPF between 9 ms - 23 ms. These discrepancies highlight the need for a more rigorous test or perhaps a grading system to specify differing levels of protection. A clearer understanding of the prime factors involved in causing injuries leading to definitive values of force or pressure, would allow these most key areas to be monitored more closely.

Although all factors contributing towards a truly representative test for taekwondo PPE could not be matched, the presented test represents an improvement in testing garments under impacts more closely matching those encountered during a competition over other currently available testing procedures.
10. Conclusions

The research reported in this thesis provides evidence in support of the development of testing protocols capable of measuring transmitted force values during impacts that more closely represent those encountered during a game situation than currently exist. Theoretical considerations are validated in practice by application through case studies based on personal protective equipment used in cricket and taekwondo. The tests were designed to prioritise the acquisition of those variables most likely to be representative of product safety. Through the development of such testing protocols it is anticipated that further work will develop a closer correlation between the mechanism for injury and the performance of protective equipment under impact which will lead to the design and development of more effective PPE, which could be better tailored to the specific needs of the sport or individual.

A cricket specific test based on an impactor representative of the size, mass and stiffness of a cricket ball being fired at game-related bowling velocities at the cricket leg guard mounted on a steel anvil attached to a force transducer, was considered. The general methodology worked to move the impact characteristics closer to those measured during an in-situ ball on human test but revealed the limitations of force transducer based force measurement under these situations. To improve the test, a novel system for measuring transmitted force was developed.

The novel system used a steel anvil of known mass suspended by bungees and instrumented with accelerometers to measure acceleration in three orthogonal axes from which the transmitted forces could be calculated. In practice the system was shown to facilitate measurement traces with considerably fewer noise artifacts than were present in the force transducer tests. This anvil was then integrated into the cricket specific test and was used to test three selected leg guards. Calibration of the force measurement system showed less than 4% uncertainty in measurements, and the variation of ball velocity of less than 3.2%, yet variation in pad transmitted force values were up to 100% over three impacts for the same impact site. The developed representative test itself performed well, demonstrating accurate force measurement under a high force short duration impact.

Three variables other than the transmitted force values were also monitored, these were the COR, deformation and contact time. These were measured during post-processing of high speed video footage.
taken of the impacts. Quantification of how close the developed representative testing protocols approached a real game cricket ball impact with a leg guard mounted on a human was achieved by comparing these three variables during a representative test and during a game situation impact. Deformation during the two impacts was similar but contact times were half during the laboratory test and COR values were double. Matching the most important variables of impactor velocity and mass to approach a representative test did not result in all characteristics of the impact being matched exactly. The representative test developed is still a significant improvement over other protocols in the literature in terms of testing the equipment under game-like impacts.

In order to mimic a taekwondo roundhouse kick delivered to a human, a mechanical simulator was designed to impact a hogu mounted on a torso shaped anvil instrumented with accelerometers in order to measure the transmitted force. Using this equipment a representative test for taekwondo PPE was developed. Work measuring the force profile of a human on human roundhouse kick was available in the literature, for these reported kicks the transmitted peak force reached a value of 4 kN, the time to reach this value was around 5 ms and the overall impulse time was approximately 40 ms. This force profile represented an ideal for the mechanical simulator to reproduce.

The mechanical simulator kicking leg was designed to be 10.06 kg where a 50th percentile humans’ leg is 12.40 kg, their effective masses were designed to be the same at 4.05 kg. The motor specification allowed the leg to be accelerated to relative kicking velocities of humans. The force acquisition system and mechanical simulator were designed to be used in conjunction; the force acquisition system used a similar accelerometer based force measurement as that proposed for the cricket test. The tower design developed for the force acquisition system removed three degrees of freedom from the system but was also found to introduce vibration back into the measurements. The human on human roundhouse kick data was not initially matched accurately at representative impact velocities, but by prioritising the peak force and time to reach it as the indicators of injury potential, it was found through experimentation that by impacting at 200 deg/s (3.32 m/s) these variables were matched closely.

A representative testing protocol for taekwondo was developed using the designed equipment. Testing was performed on 9 hogus. 5 commercial hogus, 2 electronic scoring hogus, 1 custom hogu and one coach’s protective pad. Significant differences were found in performance in terms of both the transmitted peak force
values and in the time to peak force values with values ranging between 0.5 kN – 7.5 kN and 9 ms – 23 ms respectively despite the potential of over-reporting force values by 17% inherent in the system established during calibration. The mechanical simulator and force acquisition system used in these tests represent the only reported attempts at producing and measuring force data in an accurate and repeatable way so as to mimic the impact of a martial arts kick.

Outcomes from the project include the novel system of force acquisition and the custom hardware itself. The accelerometer based system for force measurement provides a novel approach to measuring force which avoids many of the problems associated with force transducer usage. The implementation of this system into cricket resulted in the representative lower leg anvil itself being a tangible outcome of the work. Both the mechanical simulator and the force acquisition system used in the taekwondo representative test are outcomes of the work and represent the only system in the world capable of mimicking human kicks and measure performance under these impacts. Although the kicking robot was designed to simulate a human roundhouse kick, it can be used to simulate other kicks or blunt impacts by varying the mass of the leg, the end effector and the velocity of impact. The force acquisition system has flexibility built in so the anvil can be changed to represent all manner of impact surfaces and anvil size and shapes.

Research reported here has shown that more complex tests can be reliable and repeatable when carried out in the lab. Using these testing protocols differences in performance between commercially available products have been highlighted. Within the literature, a true mechanism for and indicator of injury are unclear but as this area of research grows, development of representative style tests will allow these true indicators of injury potential to be used in conjunction with realistic game impacts to fully optimize PPE for sport.
11. Further Work

Although the work reported in this thesis has succeeded in achieving its primary aims, it is important to consider its contribution to the broader aim of understanding and protecting against on-body impacts in sport. This thesis has demonstrated the unique circumstances that determine the impact for the two focus sports, and this has been linked to injury risk through measurement of transmitted force, but there are multiple other factors which may have an effect such as performance level of players, style of play, specifics of the participant and many more. As each of these factors is considered the complexity is increased and a range of further work is required before all aspects can be considered.

In order to achieve benchmarks for performance related to human injury tolerance, a series of representative tests was developed. Tsui (2010) reported some work in this area for taekwondo, and in Chapter 5 a series of human tests with cricket ball impacts were carried out with little consideration for injury mechanics. These tests provide information regarding the impact conditions but very little on the actual human response to blunt trauma relevant to the sports. A thorough investigation into injury mechanisms in the focus sports would allow a much clearer definition on limit loads during the testing itself, measuring transmitted force in the tests and being able to relate this to real world injuries would allow much clearer engineering outcomes for the PPE. This remains an ongoing challenge for researchers in this field.

Within this thesis, the primary measured variable throughout has been force. The peak force, contact time and time to peak force have all been used as indicators to the amount of injury which would be assumed to be inflicted on a player. With further investigation into the injury mechanisms, as suggested above, would come a better understanding of the variables which require monitoring, this in itself may require the tests developed here to be adapted in order to better quantify the protective capabilities of the PPE on test. In addition, it should be noted that early on in this investigation, work by Tsui (2010) suggested that pressure may be a better indicator of injury than force. At the time a system capable of measuring the high pressures at a high frequency was unavailable. Should a capable system be developed then further work should consider integration into the current system and use both pressure and force data to better understand the impacts being inflicted. Should a newly developed pressure measurement system be developed along the same thin film sensor technology as is currently used in pressure measurement systems, it should be possible to measure peak force, pressure and contact time during human impacts in a cricket style test.
similar to that performed in section 5.3. Knowledge of these variables could be used to establish human injury tolerances for this sport. Furthermore, should developed pressure measurement systems be integrated into either game or representative testing, there is no guarantee that these would not affect transmitted forces, again increasing the level of complexity of these tests.

The two representative tests developed within this thesis represent completely novel ways of testing items of PPE. The majority of the work involved development of the equipment to make these protocols possible. This means that the protocols themselves have significant room for refinement. A series of sensitivity studies varying impactor mass and velocity may be able to provide further improvements to how close these tests can approach real impacts. Although the repeatability of force measurement has been demonstrated through calibration, specific work monitoring the long-term repeatability of the testing protocols has not been carried out, these type of tests would be important if these protocols were to be developed into standardised tests or used more widely to within industry to more finely tune PPE performance.

As discussed in Chapter 9, the final force profile data gathered from the force acquisition system was far noisier than that from the cricket rig. These vibrations increased the error inherent in the peak force data in particular. A more elegant usage of data processing techniques, and in particular filtering, could be used to refine the raw signals and increase certainty without any major changes to the testing procedure. Alternatively, a larger undertaking may involve extensive modifications to the force acquisition system itself, refinement of the anvil and tower design looking at the vibration characteristics of the structure and attempting to design them out of the force trace.

Throughout the work, one topic that has been mentioned repeatedly is that of biofidelity. Incorporating structures and/or materials to mimic the responses of the human more closely. Throughout, the approach taken was minimise the compromise on the measurement of the transmitted force, on the basis that further deformable bodies would affect the repeatability of measurements. Considering biofidelity as a continuum, incrementally including increasing degrees of biofidelity over the long term could be used to study the response, how close a “true” representative test could be approached and to what degree this affects the repeatability of testing.
The representative testing protocols for cricket and taekwondo were designed with one specific item of PPE in mind for each. In each of these sports there are other items of PPE which would need to protect from similar impacts. In cricket, thigh guards, gloves, forearm guards, boxes and helmets all undergo the same impact conditions and could be tested using a similar test though some may require re-design of the anvil. Similarly in taekwondo, but also across all combat sports where kicking is a allowable technique, refinement of the anvil would allow impact testing of a wide range of items of PPE. With the cricket test, ball velocities are easily adjusted by changing air pressure to the ball cannon, so any sport where ball impacts can occur could be approached, hockey equipment in particular, lacrosse or baseball. The taekwondo kicking velocity can also be altered, so approximation of any swing style kicking action could theoretically be approached, this may have applicability with football shin guards and could be another area of further work.

Overall, the tests developed within this project have demonstrated that accurate measurement of force values can be achieved during complex impacts. Further development of these styles of testing across a whole host of other sports will ultimately be able to combine with more detailed understanding of human tolerance for injury. This will allow design and refinement of sports PPE to such a level where by injuries due to these impacts can be minimized.
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Appendix A

Power Spectral Density Function:

```matlab
function [px]=jonsPSD(x,showplot)
%[px]=jonsPSD(x,showplot) returns unweighted power spectrum for data with time
%values in column 1 and magnitude values in column 2
% If 'showplot' is 'y' a plot of the power spectrum will be produced

if nargin < 2
    showplot='n';
end

tinc=x(2,1)-x(1,1);
Gx=fft(x(:,2));

%Compute power spectrum
pxx=real(((1/length(Gx))^2)*Gx.*conj(Gx)); %the
% squared magnitude of the transform is obtained from the conjugate of the complex
% fx
%and is scaled by dividing by the number of points (also squared)
px(1,2)=pxx(1); %the first data
point is the dc level and is placed in first column of px
px(:,1)=1/(length(Gx)*tinc)*((1:(0.5*length(Gx)))'; %Transform is a
% mirror image about half the sample freq, it needs to be folded in half
px(2:0.5*length(Gx),2)=2*(pxx(2:0.5*length(Gx)))); %so multiply by
% 2 and divide by sqrt(2) to get rms level. Because we're working with power
% spectrum, needs to be (2/sqrt(2))^2

if showplot=='y'
    figure
    plot(px(:,1),px(:,2))
end
```

Free-body collisions using central differencing method:

```matlab
function [time,X,Xvel,Xacc,F]=model3(M,C,K,X0,X0vel,dt,showplot);
% Multi-DOF model, free vibration, linear stiffness and damping, central
difference method applied
% Positive direction defined as left to right
% Equation of motion of the form: [M]Xacc+[C]Xvel+[K]X=0
% X0 = column vector of the initial displacements of each mass e.g. X0=[0;0]
% X0vel = column vector of the initial velocities of each mass e.g. X0vel=[10;0]
% dt = time increment
% showplot = 'y' or 'n'
% For further details, see Rao(2004) Mechanical Vibrations pp. 808-818

X0acc=M^-1*(-(C*X0vel)-(K*X0));
X_1=X0-(dt*X0vel)-((dt^2/2)*X0acc);

% Displacement at time t=1
X=((((1/dt^2)*M)+((1/(2*dt))*C))^-1)*((-K-((2/dt^2)*M))*X0)-((((1/dt^2)*M)-
((1/(2*dt))*C))*X_1));
```
% Displacement at time t=2
X(:,2)=(((1/(dt^2)*M)+(1/(2*dt)*C))^-1)*((-K-((2/dt^2)*M))*X(:,1)-(1/(2*dt)*C)*X0);

% Velocity at time t=1
XVel=(1/(2*dt))*(X(:,2)-X0);

% Acceleration at time t=1
Xacc=(1/(dt^2))*(X(:,2)-2*X(:,1)+X0);

% Forces at time t=1
F=M*Xacc;

i=1;
while F(1,i)<0
    i=i+1;
    X(:,i+1)=(((1/(dt^2)*M)+(1/(2*dt)*C))^-1)*((-K-((2/dt^2)*M))*X(:,i)-(1/(2*dt)*C)*X(:,i-1));
    XVel(:,i)=(1/(2*dt))*(X(:,i+1)-X(:,i-1));
    Xacc(:,i)=(1/(dt^2))*(X(:,i+1)-2*X(:,i)+X(:,i-1));
    F(:,i)=M*Xacc(:,i);
end

end

if showplot=='y'
    figure
    plot(time,F)
    xlabel('Time (ms)')
    ylabel('Force (N)')
    legend('M1','M2','M3','M4')
    figure
    plot(time,X(:,1:end-1))
    xlabel('Time (ms)')
    ylabel('Displacement (m)')
    legend('M1','M2','M3','M4')
    subplot(3,1,2)
    plot(time,XVel)
    xlabel('Time (ms)')
    ylabel('Velocity (m/s)')
    legend('M1','M2','M3','M4')
    subplot(3,1,3)
    plot(time,Xacc)
    xlabel('Time (ms)')
    ylabel('Acceleration (m/s^2)')
    legend('M1','M2','M3','M4')
end
Appendix B

Initial kicking robot frame CAD:

Working drawing of mechanical simulator leg design:

Working drawing of kicking robot frame:
Photos of construction

Catching frame and tower:
Anvil and protective ring for tower:

Mechanical simulator set up with force acquisition system base plate:

Control box and force acquisition system:
Mechanical simulator and force acquisition system:

Gas spring catching arrangement: