THE PERCEPTION OF COMFORT AND FIT OF PERSONAL PROTECTIVE EQUIPMENT IN SPORT.

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

Doctor of Philosophy

Loughborough University

2010

ABSTRACT

During the design of sports equipment, the main focus is usually on physical performance attributes, neglecting key subjective factors such as feel and comfort. The personal protective equipment worn in sport is a typical example, where injury prevention has taken precedence over user comfort, but it is anticipated that with a new approach to the design process, comfort can be improved without sacrificing protection. Using cricket leg guards and taekwondo chest guards as an example, this study aimed to develop a systematic method for assessing user perceptions and incorporating them into the design process. Players' perceptions of the factors that influence the comfort of cricket leg guards and taekwondo chest guards were elicited through the use of co-discovery sessions, focus groups and individual interviews, and analysed through an inductive process to produce a comfort model. The relative importance of each different comfort dimension was identified through the use of an online questionnaire utilising the analytical hierarchy process method. Through the combination of these methods, six general dimensions were identified with a weighting regarding the amount to which each one determines a user's perceived comfort. For both cricket and taekwondo, the majority of players ranked 'Fit' as the most important factor affecting comfort.

Experimental procedures were developed to objectively test the 'Fit' of cricket leg guards, with regards to batting kinematics, running performance and contact pressure. These methods were combined with subjective assessments of leg guard performance, to determine if there was a relationship between users' perceived comfort and objective test results. It was found that shot ROM and performance were not significantly affected by cricket leg guards, despite perceptions of increased restriction whilst wearing certain pads.

Wearing cricket leg guards was found to significantly decrease running performance when compared to running without pads ($p<0.05$). In addition, it was found that the degree of impedance depended on pad design and could not solely be attributed to additional mass. These results correlated with the subjective assessment of three different leg guards, with respondents identifying the pad which had the largest influence on their running biomechanics and impeded their performance the most, as the most restrictive pad.

Contact pressure under the pad and straps was also measured for four different leg guards whilst running. The results found that the top strap applied the greatest amount of pressure to the leg, especially at the point of maximum knee flexion. The peak pressure under the top strap was found to reach up to three times that of any other area of the pad. These results were reflected in the subjective assessment of the leg guards, with all nine subjects identifying the top strap as an area of discomfort for certain pads. The results also suggested there was a preference for pads with a larger more consistent contact area, as pad movement was perceived to increase when contact area variation was greater.

Finally the results from this research were used to develop a product design specification (PDS) for a cricket leg guard, specifying size, mass, contact pressure and shape. The PDS was used to develop a concept design which would maximise comfort, whilst maintaining protection.

ACKNOWLEDGEMENTS

I would like to thank all those who not only made this research possible but enjoyable. Thanks go to my supervisor Dr Jonathan Roberts, for his support, encouragement, advice and most of all patience throughout this project. I would also like to thank the other academics within the sports technology research group for their support and encouragement throughout my time at Loughborough.

I would like to thank the other members of the sports technology team, including my fellow students, research associates and technicians for their friendship, advice and assistance, making it a productive and enjoyable environment to work in. A huge thank you must go to British taekwondo, the English cricket board and Loughborough university cricket clubs for providing facilities and subjects for a variety of tests.

I would like to thank my parents, sister and my fantastic friends for all their support and encouragement throughout my education. Finally I would like to thank Sarah, who has helped and supported me every step of the way.

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J. M. Webster and J. Roberts. Incorporating subjective end-user perceptions in the design process: a study of leg guard comfort in cricket. *Proc. IMechE, Part P: J. Sports Engineering and Technology*, 2009, 223 (No. 2), 49-62.

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"Understand to achieve anything requires faith and belief in yourself, vision, hard work, determination, and dedication."

Gail Devers

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NOMENCLATURE

PPE	Personal protective equipment
Hogu	Taekwondo chest guard
VOC	Voice of the consumer
QFD	Quality Function Deployment
P	Pad
WC	Weighted comparison
AHP	Analytical Hierarchy Process
n	Number of General Dimensions
C	Element of analytical hierarchy process
a_{ij}	Comparison between elements i and j
a_{ji}	Reciprocal of a_{ij}
w	Weighting
CI	Consistency index
CR	Consistency ratio
RI	Random consistency
B_{ca}	Biased corrected accelerated
N	Number of subjects
k	Number of conditions/ samples
T	Friedmans test statistic
LSD_{rank}	Least significant difference rank
ROM	Range of motion
3D	Three-dimensional
2D	Two-dimensional
CODA	Cartesian optoelectronic dynamic anthropometer
LED	Light omitting diode
UCCE	University centre of cricket excellence
AJC	Ankle joint centre
KJC	Knee joint centre
LKA	Left knee angle
RKA	Right knee angle

LAA	Left ankle angle
RAA	Right ankle angle
LKJC	Left knee joint centre
RKJC	Right knee joint centre
LAJC	Left ankle joint centre
RAJC	Right ankle joint centre
x	x-axis
y	y-axis
z	*z-axis*
ApEn	Approximate entropy
GRF	Ground reaction force
ANOVA	Analysis of variance
COP	Centre of pressure
BW	Body weight
Xcorr	Cross correlation
FFIC	Front foot initial contact
FFTO	Front foot toe off
BFIC	Back foot initial contact
BFTO	Back foot toe off
PDS	Product design specification
CAD	Computer aided design

Chapter 1

Introduction

Over the past two decades, there has been significant growth within the sports industry, resulting in an increased demand for sporting equipment. This increase in demand has resulted in the formation of several conglomerates within the industry, including multi-billion pound organisations such as Nike, Adidas, Puma and Brunswick Corporation (Lipsey, 2006), all of which are vying to be the largest sporting goods manufacturer in the world. Because of this increased competition within the sports equipment and apparel market, manufacturers are constantly trying to improve the performance and comfort of athletes through the development of new products. To date, the majority of research has focused on increasing performance through enhanced power, speed, or accuracy, with less emphasis placed on evaluating perceptions of comfort, even though the user's subjective assessment ultimately determines their satisfaction with a product and their perception of the brand. Customer satisfaction is a phenomenon that typically occurs when the perceived performance and benefits of a product exceed the expectations of the customer (Peter and Olsan, 2005) and it is widely accepted that customer satisfaction levels and long-term brand loyalty are influenced by emotions during and after the use of a product (Barsky and Nash, 2002). Comfort has been identified as having a major influence on these emotions, as it is influenced by the state of mind that the individual is in (Vink, 2005) and could be a key determinant when selecting a sports product.

One area within the sports equipment market which has been subject to significantly less research regarding comfort and end-user satisfaction is protective clothing, despite several sports with large numbers of participants, such as cricket, martial arts, American football, baseball and ice hockey, depending on it. The lack of research within this area is surprising given the high level of interaction between the participants and their personal protective equipment (PPE). In many cases, PPE covers large areas of the body and incorporates multiple articulating joints, which are vital in performing necessary motions within the sport. PPE, therefore, could have a significant affect on both perceived comfort and sporting performance. Despite this, the majority of research into the comfort of PPE has been based within industry, military settings and the services (police and fire-fighters), with sports garments having been researched with significantly less frequency.

Historically in industry, PPE has been designed to maximise protection of the wearer, with comfort considered to be of secondary importance (Stull 2000, Zimmerli 1996, 1998). This has resulted in bulky, cumbersome and ill-fitting PPE, which has been found to degrade performance as a result (Cox et al., 1981; Draper and Lombardi, 1986; Johnson, 1991). This degradation of performance could ultimately result in PPE being discarded, increasing potential risk of injury. Dissatisfaction with PPE can result from thermophysiolgical discomfort, reduced work efficiency or impeded movement (Shanley *et al.*, 1993). The degree of dissatisfaction with PPE was investigated by Akbar-Khanzadeh *et al.* (1995), using respiratory masks as an example. Akbar-Khanzadeh *et al* (1995) found that only 8% of users described their PPE as being comfortable, with 92% of respondents found to be dissatisfied with the equipment.

As research has advanced, it has been shown that comfort and fit are not just luxuries for PPE but key safety features (Stull, 2000; Zimmerli 1996, 1998), as a high level of discomfort can result in equipment being discarded. Despite this, sports PPE research has followed the same trend as industrial research, focusing on maximising protection and athletic performance, with comfort being of secondary importance. Various studies have been conducted investigating different performance measures such as protection levels, running speed and agility (Blair *et al.* 2008; Green *et al.* 2000, Loock *et al.* 2006). The performance of different baseball chest protectors has been assessed in terms of protective properties and rebound characteristics (Blair *et al.* 2008). The results identified that there were no significant differences in protective performance between different chest protectors; however, transmitted force and rebound speed did vary depending on impact location. Green *et al.* (2000) also measured the effect of sports PPE on performance by focusing on speed and agility. This paper revealed that knee braces affect running speed and turning manoeuvres that are typically associated with American football. Loock *et al.* (2006) also measured the effect of PPE on running and turning performance but in cricket. Their results suggested that running and turning times were not significantly affected by different leg guards despite a difference in mass. Although these papers focus on evaluating existing products in terms of performance, they do not consider perceived comfort or end-user satisfaction. The lack of research regarding the comfort of PPE was particularly apparent when considering the design of Australian football protective head gear (Braham *et al.* 2004). Braham *et al.* (2004) identified that the use of protective headgear will significantly reduce head injuries such as lacerations and could reduce the susceptibility of players to concussion. Only 2.1% of players however, wear protective headgear, with 45% of footballers stating that they would not wear it as it was "too uncomfortable". These results suggest that further consideration of end-user comfort and satisfaction is required when developing PPE.

Numerous definitions of comfort exist, although all definitions convey a similar message to that outlined by Slater (1985, p.4), who defined comfort as "a pleasant state of physiological, psychological and physical harmony between a human being and the environment". When considering clothing comfort, previous research has maintained the idea that the interaction between the individual and the environment having a significant affect on comfort. This suggests that the overall state of satisfaction is a result of a balance between physical, social psychological and physiological factors, whilst identifying the significant affect of the clothing system (Branson and Sweeney, 1991).

1.1 Comfort Models

Early research suggested that there are three main components of comfort: the individual, the environment and clothing, and that their interaction influences the feeling of comfort (Fourt and Hollies, 1970). Within this model, variables were presented for each of these components with different measurement methods and units being developed for each variable. When considering the individual, the key variants given were metabolism, evaporation, surface temperature, rectal temperature, tympanic temperature, DuBois surface area and heart rate. Clothing variables were thermal insulation, resistance to evaporation, wind resistance, thickness, weight and surface area. Finally, the environmental variables included temperature, relative humidity, air movement and radiant heat (Fourt and Hollies, 1970). This delineation of the variables within each component was seen as the greatest contribution to the understanding of comfort. It did, however, focus on the protective and functional aspects of comfort, omitting both general and social-psychological aspects.

The Fourt and Hollies (1970) comfort model was then refined through three further developmental stages. The first developmental stage was entitled "Comfort's Gestalt" by Pontrelli (1977), where the term "Gestalt" was deemed appropriate for the complex construct of comfort, due to its inherent meaning of "a configuration of physical, biological, or psychological phenomena so integrated as to constitute a functional unit with properties not derivable from its parts in summation" (Merriam-Webster, 2002, pp.160). Pontrelli's model included the concept of a comfort triad developed by Fourt and Hollies (1970), but also introduced a psycho-physiological variable which included additional factors such as tactile, aesthetics, state of being and fit (Figure 1.1). Another key development within Pontrelli's model was the inclusion of stored modifiers, which were included as a filter, conceptually allowing the physical and psycho-physiological variables to be combined to ultimately determine the user's comfort level. The so called stored modifiers consisted of an individual's past experiences, pre-conceptions, and prejudices which allowed the subjective responses to be validated.

The comfort model was further developed by Sontag's (1986) "Human ecological approach" which maintained Fourt and Hollies' comfort triad and Pontrelli's stored modifiers. Sontag's model developed Pontrelli's work by moving away from a segmented model with a clear separation between the physical and psychological aspects of comfort, to a more interactive and combined model as depicted in Figure 1.2. The model demonstrates the individual component of the comfort triad being encapsulated by the clothing attribute, which is in turn encapsulated within the environmental component. Each of the dimensions includes an expanded list of variables based on the previous work of Fourt and Hollies (1970) and Pontrelli (1977), with the stored modifiers being included within the person variables, due to them being based on an individual's past experiences. Finally, a double ended arrow was used to represent the interactive nature of the three components in determining perceived comfort. The major contribution of Sontag's work was the concept that each component of comfort is separate but inter-related, and the idea that there are physical, social and psychological aspects within each component of the comfort triad.

The final developmental stage to date was proposed by Branson and Sweeney (1991), further building on the work previously discussed, maintaining the comfort triad, stored modifiers and the idea that there are both physical and social-psychological factors affecting comfort. The model by Branson and Sweeney, illustrated in Figure 1.3, shifted focus away from the triad being the main categorization mechanism, stating that each component has a physical and a social-psychological dimension. These two dimensions are used as the organisational structures for the three components of the triad; Table 1.1 lists the physical and social-psychological factors included for each component of the comfort triad. The idea of a Gestalt proposed by Pontrelli (1977) has been maintained within this model by the use of broken lines, representing the influences of each subcomponent on each other, highlighting the importance of the interaction between different aspects of comfort. Although the Branson and Sweeney model (1991) is a general comfort model, it can be applied to PPE, as the majority of physical, clothing and environmental attributes are relevant. For example, an individual's mass/ size, body image and the fit of a garment will significantly affect their perceived comfort when considering the majority of garments.

Person Attributes		Clothing attributes		Environment Attributed	
Physical Dimension	Social psychological dimension	Physical Dimension	Social psychological dimension	Physical Dimension	Social psychological dimension
Sex Age Race Weight Height Physical condition Activity Exposed surface area	State of being Self concept Personality Body image/cathexis Values Attitudes Interests Awareness Religious beliefs Political beliefs	Fabric Characteristics: Fibre Content Yarn Fabric structure Finishes Colour Fabric/clothing system Heat transfer properties: Moisture/vapour transfer properties Air permeability Clothing system: Fit Design	Fabric/ clothing system Aesthetics Style Fashionability Appropriateness Design Colour Texture Body emphasis/ de-emphasis	Air temperature Radiant temperature Wind velocity Ambient vapour pressure	Occasion/ situation of wear Significant other Reference group Social norms Cultural patterns Historical precedence Geographic locale

Table 1. 1: Physical and social-psychological dimensions of clothing (Branson and Sweeney, 1991)

The Branson and Sweeney model acknowledges that comfort is not just physical but psychological, and this is supported within the literature (Rutherford-Black and Khan, 1995). Li and Wang (2006) stated that comfort is a multi-dimensional, complex construct which has a number of both physiological and psychological areas to consider. From the original conceptual models, four main aspects have been identified in influencing perceived comfort (Akbar-Khanzadeh *et al.*, 1995, Fan and Chen 2002, Li and Wang, 2006):

1. Thermal comfort (thermophysiolgical comfort)
2. Sensorial comfort (tactile comfort)
3. Body movement comfort (fit and freedom of movement)
4. Aesthetic appeal

These aspects were also identified by Schutz *et al.* (2005), who identified garment factors contributing to overall satisfaction, through the use of focus groups, listing fit (body movement comfort), thermal comfort, appearance (aesthetic appeal) and feel (sensorial comfort) as the major characteristics needing to be considered. Through these facilitated discussions, a list of factors important to comfort were generated and refined. Abrasiveness, softness, and coarseness, were all found to be aspects of sensorial comfort. Thermal factors included absorbency and breathability, whereas thickness, weight, stiffness, and clinginess of the material fell under body movement comfort. Within the studies conducted, these four aspects affecting comfort have consistently appeared, but the influence of each one and whether these influences are present within every situation, have not been investigated.

There are many physiological and psychological interactions that affect aesthetic appeal, thermal, sensorial and body movement comfort, with the overall feeling of comfort being generated due to these. The physical considerations of comfort include thermal comfort, taking into account the transport of both heat and moisture (Li 2005, Plante *et al.*, 1995), mechanical interactions between clothing and body, and neurophysiologic response mechanisms. The psychological aspects are concerned with the processes by which perceptions are formed from sensory responses to physical stimuli. Li (2001) produced a flow chart to represent the different interactions of each aspect concerned (Figure 1.4). The flow chart represents the process through which overall perceptions of comfort are formulated and modified. This is based around the 'Comfort's Gestalt' model (Pontrelli,1977) focusing on the three variables identified as physical variables of the environment and clothing; psycho-physiological parameters of the wearer; and psychological filters of the brain. The physical processes stimulate the sensory organs within the human body, which respond by generating neurophysiologic signals, these are sent to the brain, which processes the information and reacts accordingly, for example adjusting sweat rate. The brain will then process the sensory signals formulating subjective perceptions of the individual sensations, and in turn contrast these against experiences/ desires, leading to an overall perceived comfort. This model demonstrates how the perception of comfort is generated, however, it does not convey the weighting each aspect has on comfort, and therefore more information is required to increase understanding of the construct.

1.2 End-user satisfaction

In the wider field of product development, numerous approaches have been advocated for incorporating the 'voice of the consumer' (VOC) into the design process, such as quality function deployment (QFD) and Kansei engineering. Ulrich and Eppinger (1995) discussed the methodological requirements for identifying customer needs and proposed the following aims for a successful method:

(a) to ensure that the product is focused on customer needs;
(b) to identify latent or hidden needs as well as explicit needs;
(c) to provide a fact base to justify product specifications;
(d) to create an archival record of the needs activity of the development process;
(e) to ensure that no critical customer need is missed or forgotten;
(f) to develop a common understanding of customer needs among members of the development team.

Through the adoption of these methodological considerations it is possible for a channel of information between the target consumer and product developers to be established, allowing interaction between them to aid in the development of a more suitable product. Several methods have been used within product development to help bridge this gap between the end-user and the design team.

Kansei engineering involves the identification of product features that influence consumer satisfaction through the use of product semantics, i.e. words or expressions describing product attributes that are collected from interviews, articles, web pages, advertisements, etc. (Alcantra *et al*., 2005). Underlying patterns in the semantic space can then be obtained by analysing subjects' product ratings obtained from semantic difference scales formed from the identified words (Van Lottum *et al*., 2006). Although this process highlights product attributes that influence consumer perception, little detailed information on the individual attributes is obtained and limited understanding is derived regarding complex consumer needs.

The aim of QFD is to deploy the VOC throughout the design process by relating product features to consumer needs (Barrass *et al,* 2008). QFD is aimed at improving three product metrics: development cost, time to market, and the customer's perception of the product's quality (King 1987). QFD is more of a development tool that builds on consumer needs that have to be identified in advance. Although QFD does provide a basic framework for concurrent design activities, it gives the designer little guidance as to which customer requirements are most important, whilst simplifying relationships between design features to positive or negative interactions. Therefore, a more in-depth user-driven approach is required, to develop an understanding of key design features and the way that they interact to determine perceived comfort.

1.3 Research objectives and proposed approach

Throughout the four developmental stages of the comfort model there have been significant advances in knowledge, with Branson and Sweeney (1991) combining the three previous models into a more organised and structured model. This general model provides information on possible factors which are likely to affect perceived comfort, however, when considering the design of individual items of clothing or PPE there is a need for a more detailed specific comfort model.

The development of specific models is particularly important when considering sports PPE due to the inherent differences of each sport, such as duration, intensity and clothing. Therefore, the first aim of this thesis was to develop a specific comfort model for individual items of PPE, determining specific design features and individual variables affecting perceived comfort, their interaction and their relative importance. The second aim was to develop appropriate objective tests which can be used to measure the affect of specific design features on perceived comfort, and in turn use this data to develop a product design specification for cricket leg guards aimed at optimising the comfort and satisfaction of the end-user. This will be done through eliciting and analysing subjective perceptions, allowing for a greater understanding of players' needs and expectations. This understanding will allow for the development of objective tests, which can be used to assess the comfort of PPE, leading to the development of concept designs aimed at maximising both comfort and protection. For this thesis the items of PPE analysed were cricket leg guards and taekwondo chest guards (Hogu). These two items of PPE were selected as they are used within very different sports, varying in intensity, duration, environment and type of impacts that they protect against.

Within this new approach there will be opportunity for key design features to be identified, which are perceived to affect the comfort of specific items of PPE, in particular cricket leg guards and taekwondo chest guards, with the relative importance of each factor to be assessed to aid in the development of new products, which aim to maximise comfort. In order to determine the relationship between end-user perceptions and physical design parameters a series of objective tests will be developed to help quantify perceptions of comfort through physical determinants. Therefore, the objectives of this thesis are to:

- Review and develop techniques for eliciting and analysing player's perceptions of PPE

- Identify important characteristics of the equipment

- Develop objective and subjective test methods to assess comfort
- Provide a detailed set of design criteria for a product design specification
- Develop a concept design that maximises comfort and end-user satisfaction.

1.3.1 Thesis outline

This thesis is comprised of seven subsequent chapters, documenting the methods, results and conclusions of five main studies and the development of a concept leg guard design for cricket. Within each chapter, relevant literature is discussed regarding each specific study in terms of methodology and previous findings in the related field. The outline of the thesis is as follows:

Chapter 2 details the results of the subjective analysis performed on cricket leg guards and taekwondo chest guards. End-user responses are structured into a comprehensive comfort model, allowing the dimensions which are perceived to affect comfort, and possible links between dimensions to be identified.

Chapter 3 focuses on the further development of the comfort model, presenting the results of an analytical hierarchy process (AHP) that determined the relative importance of each comfort dimension. Comparisons between cricket leg guard and taekwondo chest guard models are performed to determine if individualised models are required for different items of PPE or whether one model can be representative of all equipment.

Chapters 4 and 5 describe the development of appropriate test methods for assessing the effect of cricket leg guards on range of motion. Chapter 4 focuses on the development of an appropriate methodology aimed at assessing the effect of leg guards on shot performance, whereas Chapter 5 assesses running performance.

Chapter 6 details the final set of objective tests performed on the cricket leg guards assessing the interaction between the pad and leg. Measurements of skin contact pressure under the pad whilst running are analysed in terms of contact area, peak and average pressures under different areas of the pad.

Chapter 7 combines the objective and subjective data into a product design specification (PDS) from which the development of a concept design for a cricket leg guard is presented.

Chapter 8 discusses the conclusions which can be drawn from this work and possibilities for further work.

Chapter 2

Development of a specific comfort model

2.1 Introduction

The first stage of the project was to determine the product characteristics and design parameters that are critical in determining the perceived comfort of the end-user. To achieve this, suitable research techniques were required for eliciting and analysing product characteristics, allowing the target market to be included in the early stages of the design process. Several techniques have been developed within the design industry to incorporate the end-user and focus product development on factors that are key to increasing user satisfaction. A common limitation with these methods, such as Quality Function Deployment (QFD), Kansei engineering and Repertory grids, is the manner in which user perceptions are collected and analysed, as discussed in section 1.2. Although these methods are deemed suitable for assessing user satisfaction, the construct of comfort is so complex and inter-related a more detailed analysis of users' perceptions is required.

The majority of comfort literature focuses on subjective responses collected using questionnaires containing categorical and continuous scales (Akbar-khanzadeh *et al.* 1995, Kujit-evers *et al* 2004). Other psychological tools allow much more rich, detailed and descriptive data to be collected, which is more appropriate for understanding perceived comfort. Within sports psychology, a method has been developed for investigating players/ user perceptions and has been implemented in a wide range of studies. This methodology was developed by Scanlan *et al* (1989a, 1989b) allowing information rich qualitative data to be acquired through interviews utilising open ended questions. The data was analysed through a technique known as inductive analysis, structuring the data into significant components through a method known as clustering. The process of clustering was used to condense the raw data through the uniting of quotes with similar meaning into representative base themes. This process was then repeated with the emergent themes grouped together to produce higher level themes until no further grouping could occur. The highest level was referred to as a 'General Dimension'. Within this clustering process, the themes identified at each level should be inclusive, in that they are representative and adequately capture the information represented by their lower order themes and incorporated quotes. This method was developed by Scanlan *et al* in 1989 and demonstrated using an investigation into the sources of enjoyment and stress for elite figure skaters. Similar methods to the one outlined by Scanlan *et al.* (1989) have been utilised within both sports psychology and sports technology. Within sports psychology inductive analysis has been used to assess the underlying properties of stress in sport (Thatcher and Day, 2008), stressors and coping strategies employed by premier league academy footballers (Reeves *et al.* 2009) and to collect information on the acquisition of high-level performance (Côte *et al.* 2005). Within sports technology research, similar methods have also been used to aid product development, including studies looking at the assessment of golf clubs (Roberts, 2002), hockey pitches (Young *et al.* 2005) and tennis balls (Davies *et al.* 2003).

Although this methodology is seen as an appropriate way to build and develop knowledge regarding player perceptions, a key limitation was identified by Roberts (2002) due to a lack of interactivity between the dimensions. As a result, Roberts (2002) developed an additional analytical stage, known as Structured Relationship Modelling, which facilitated the exploration of possible interactivity and links between different general dimensions and lower order themes. The addition of this stage allowed a more representative model to be developed, identifying perceived interaction between different dimensions. Since the development of this method, the process of structured relationship modelling has been used to assess players' perceptions of tennis balls (Davies *et al*, 2003), tennis grips and handles (Barrass *et al*, 2005) and hockey pitches (Young *et al*, 2005).

This analytical procedure was deemed suitable for developing an accurate and appropriate comfort model representing the end-users' perception because it enables subjects to analyse the product whilst using it, eliciting responses regarding characteristics they like as well as dislike. Another advantage of this method is that it is extremely flexible, as it is led by the subject, minimising constraint. Also it enables inter-dimension relationships to be identified, highlighting possible affects and consequences of altering specific design features.

This study aimed to develop a specific comfort model for cricket leg guards and taekwondo chest guards, enabling the identification of features which are perceived to be key in determining perceived comfort, and compare the two models to determine whether a comfort model specific to individual pieces of PPE was needed or whether one model could represent all protective garments.

2.2 Study Design and Test Methodology

A modified version of the study design process used by Roberts *et al* (2001) (illustrated in Figure 2.1) was used to provide a logical and structured approach to the study. The design process was modified to include methodological triangulation.

2.2.1 Triangulation

Within qualitative research a key issue which has consistently been identified is the trustworthiness of the data, and how to assess this. According to Schwandt (1996) the criteria for qualitative enquiry are standards, benchmarks and regulative ideals which can be used to guide judgements about the quality of the inquiry processes and the findings reported. However, the rise of different methods of inquiry and areas of research has led to two distinct views on the criteria which should be used to assess the 'quality' of the data presented. These two persuasions focus on the micro level of interaction, where 'immanent-essentials' are considered and used to inform the research review process. The first persuasion is criteriology, where qualitative research is identified as an alternative paradigm to quantitative or post-positivistic research, therefore, requires a set of its own pre-set, unique, permanent and universal criteria to assess its quality (Sparkes, 1998). Lincoln and Guba (1985) outlined a strong set of criteria for assessing work within the paradigm of naturalistic enquiry, advocating prolonged engagement, persistent observation, triangulation, peer debriefing, negative case analysis, referential adequacy and member checks, with a combination of these methods ensuring the quality of the research. Sparkes (1998) identified several limitations within the criteria identified by Lincoln and Guba (1985), stating that the use of multiple methods alone can not ensure trustworthiness.

Relativism has been identified as a parallel perspective, however, as with criteriology it does identify the need to use criteria to judge qualitative research, but it states that this criteria should not be pre-defined or universal (Sparkes, 2009). The relativism persuasions states that judgements about qualitative research are time and place dependent, unlike quantitave measurements which are deemed to be independent of both time and place. Smith and Deemer (2000) also identified that any list of criteria is always open-ended and can be modified depending on the context and purpose. Within this research fundamentals from both perspectives were utilised to maximise the impact and trustworthiness of the data. Within the data collection triangulation was used as discussed within the criteriology paradigm to help maximise the validity and reliability of the results through the combination of different methods, however, the list of criteria to assess the data was open ended allowing for further criteria to be added if deemed necessary when determining the accuracy and validity of the data in accordance with relativism.

The primary reason for the inclusion of triangulation within the experimental design is the recognition of the inherent strengths and weaknesses of every research method. The notion of triangulation, is that the greater number of methododologies, investigators, data sets, or environments used, the greater the confidence in the results, as the deficiencies of each approach are compensated for (Blaikie, 1991; Oppermann 2000). If the same conclusion can be drawn from the different methods, locations, investigators, environments and data, then the results can be deemed reliable and valid (Guion 2002). Alternatively if the results contradict each other, the validity of the results and methods used needs to be questioned. The integration of different methods produces a more realistic and fuller picture of the area of interest.

As well as methodological triangulation, investigators have used data triangulation where different types of data are collected to give a broader, more in-depth understanding and knowledge base. Alternatively investigator triangulation benefits from different investigators conducting the same methods, theory triangulation involves the use of multiple professional perspectives to interpret a single set of data, and finally, environmental triangulation uses a variety of locations to conduct the testing (Guion, 2002). A combination of all forms of triangulation within testing provides the most reliable and valid results due to its compensation for all possible weaknesses within the data collection and analysis process. Therefore, within this study a combination of methodological, environmental and investigator triangulation were used.

2.2.2 Participant selection

The selection of participants for a study has a direct bearing on the quality of data collected and is therefore an important consideration (Patton, 1990). For this study, the technique of purposeful sampling was used, as it has been shown to be a powerful tool due to the manner in which information rich cases are selected for in-depth analysis increasing the quality and depth of response. Information rich cases are those from whom a great deal can be learned about issues of central importance to the research question (Patton, 1990).

Elite level cricketers were deemed the most suitable for this study because of the amount of time spent wearing cricket leg guards during training and match play. They also generally represent what are known as 'lead users' and are considered to be more effective at identifying key features, product needs, and inadequacies of equipment (von Hippel, 1988).

Sample size is another key consideration, as a small sample size can result in data that is not representative of the population, whilst a large sample size will increase test time and labour costs incurred. In qualitative research, the experts' views on sample size are often ambiguous, and conflicting. Studies of a similar nature to this discovered that data saturation occurred between fifteen and twenty interviewees' (Barrass, 2008; Davies *et al*, 2003; Hanton and Jones, 1999; Harwood, 1997; Roberts *et al*, 2001). This is consistent with the views of Griffin and Hauser (1993) who considered ten participants too few and fifty too many. Based on this, twenty cricketers with a mean age of 19.9 years (±1.7

years) participated in this investigation, sixteen within the initial testing and four in the validation process. All participants played at either County 1st or 2nd team level, or an equivalent standard, and were top order batsmen.

2.2.3 Data Collection

A variety of data collection techniques have been utilised across a broad range of subjects in qualitative enquires, and all have different strengths and weaknesses (Table 2.1). This study, therefore, incorporated the techniques of methodological triangulation to compensate for known limitations of different data collection techniques, and increase the validity and reliability of the results. Jordan (2000) reported that the most common data collection methods within qualitative studies are private camera conversations, co-discovery, focus groups, think aloud protocols, reaction checklists, questionnaires, interviews, and participative creation. After consideration of each method's strengths and weaknesses, as summarised in Table 2.1, the three methods selected for use within this study were co-discovery, focus groups and interviews. These three methods were selected as they include group and individual interviews, where the investigator is both present (focus group and individual interviews) and absent (co-discovery) from the room whilst data is collected.

The test procedure began with a co-discovery session involving a group of five or six players with no investigator present. The players were asked to evaluate six pairs of pads, which were chosen as a representative sample of the market (Figure 2.2), and discuss the positive and negative attributes of the pads, and the features they would change to increase comfort. The co-discovery sessions lasted approximately twenty minutes and the discussions were recorded for further analysis. This method was used as the initial method for data collection as it allowed participants to express their thoughts and feelings without being influenced by the investigator. Co-discovery also provided freedom with which participants could talk, resulting in discussions covering much wider aspects of the product compared to other methods (Vries *et al,* 1996). Conversely, the lack of investigator input can cause the data collected to be irrelevant and limit the usefulness of the findings, increasing cost and time. Variations between different sessions will also be large using this method as there is no set structure causing analysis to be extremely complex and more susceptible to error (Jordan, 2000).

Following the co-discovery session, each participant was required to use two different types of pad (allocated at random) for 5-10 minutes, facing a minimum of 10 balls in each pad during a typical net session. The players were encouraged to run between the wickets when they felt they had hit a scoring shot. They were also asked to pad several balls away allowing for a complete assessment of each pads performance. No control pads were used to reduce kinaesthetic after-effects preventing fixations on certain stimuli and augmentation/ reduction of sensations (Ashdown and DeLong 1995). Once each player had completed the practical testing they participated in a focus group.

Focus groups followed practical testing of the pads as previous research has demonstrated the effectiveness of combining a practical element within the interview process to stimulate more responses from participants, rather than merely relying on retrospective analysis of products (Roberts *et al*., 2001). Focus groups were deemed to be a suitable secondary data collection method due to the flexible structure typically employed, as participants are allowed to explore different areas of importance to them. Also the dynamics and interactions between group members can be used to help stimulate ideas, further developing the productivity of the participants; which has become known as the "group effect" (Morgan 1993). The purpose of using a focus group was to "learn through discussion about conscious, semiconscious and unconscious psychological and sociocultural characteristics and processes" (Berg 2001). This method reduced expense and time because fewer interviews need to be conducted, whilst an increased confidence in results was gained through the emergence of patterns (Patton 2001). It has been suggested that focus groups are more efficient than individual interviews as the findings from a focus group outweigh the sum of the findings from individual interviews due to the conversations stimulated between participants, the way interactions can be observed, and the strength of agreement that can be analyzed (Morgan and Krueger, 1993, Patton, 2001). Ferns (1982) suggested that two eight-person focus groups would produce as many ideas as 10 individual interviews, highlighting the efficiency and effectiveness of focus groups. Krueger (1994) indicated that, although the use of focus groups can be beneficial in the identification of common themes, they are less useful in micro-analysis of subtle differences and therefore, would be more beneficial in providing an overview of a construct or product rather than in depth analysis. Unlike co-discovery, the interviewer directs the discussion which increases the relevance of the findings, but has the potential to influence the participants' responses; this influence is not confined to focus group testing.

	Private camera	Focus group	Co-discovery	Think aloud protocols	Questionnaires	Interviews	Participative Creation	Reaction checklists
Flexibility to vary content, sequence and wording of questions	Limited	Extensive	Limited	Extensive	Limited	Extensive	Extensive	Limited
Opportunities for probing	None	Extensive	None	Extensive	Limited	Extensive	Extensive	Limited
Number of respondents'	Average	Average	Limited	Limited	Extensive	Limited	Limited	Extensive
Emphasis on writing skills	Limited	Limited	Limited	Limited	Extensive	Limited	Limited	Limited
Rate of return	Average	Extensive	Extensive	Extensive	Limited	Extensive	Extensive	Limited
Cost (time/ resources)	Extensive	Average	Extensive	Extensive	Limited	Extensive	Extensive	Limited
Influence of investigator	Limited	Extensive	Limited	Extensive	Extensive	Extensive	Extensive	Average
Freedom of participant	Extensive	Average	Extensive	Average	Extensive	Limited	Limited	Extensive

Table 2. 1: Comparison of qualitative data collection methods.

For the focus groups, a naturalistic approach was used, due to this research being of an explorative nature. Naturalistic inquiry was deemed suitable due to theory being posteriori rather than priori. This is considered beneficial in exploratory research (Erlandson *et al.* 1993) as it minimises investigator bias and restraint on subjects' responses, allowing for a more detailed and representative reflection of subjects' perceptions. A framework for the focus group session was developed in the form of an interview guide, which outlined a list of possible questions. Although some questions were set, the direction of the discussion was determined by the participants' responses. Open ended questions were used because of the greater understanding gained through them (Takemura *et al.* 2005), allowing the researcher to gain a more insightful reflection of the participants perceptions, whilst capturing their view point without predetermined biases influencing the results (Patton 2001). The interview guide is discussed in detail in the next session.

2.2.4 Interview Guide

The focus group sessions were semi-structured using an interview guide (included in Appendix 1), to provide a basic outline for the interviewer to follow (Thelwell *et al.* 2008). The guide consisted of nine questions that were used to initiate conversation when the discussion was appearing to come to an end or a topic had become exhausted. These questions were worded to be non directive to prevent participants from being led into answers or discussions, an example of specific questions used to help encourage player responses include:

> Was there any noticeable difference between the pads used today
> regarding comfort? If so what?

After the initial question had been asked the interviewer had complete freedom and flexibility to explore and probe the participants' responses. Topics were only discussed if they had been introduced by the participant, to limit investigator bias.

All testing was conducted at the facilities where the players regularly trained placing them in a familiar and relaxed environment. The pads utilised within the practical test were displayed to aid discussion between different participants and to allow players to demonstrate what they were trying to purvey, providing the investigator with a greater understanding. The investigator was permitted to probe statements made by the respondent, to seek clarification and to promote further discussion of topics of interest.

For this investigation, a pilot study was conducted in order to assess the suitability of the data collection method; from the pilot test a number of modifications were made to help the focus groups flow. All methods used within this study were approved by the Loughborough University ethics committee prior to testing.

2.2.5 Data analysis

There are two main approaches commonly used when organising raw qualitative data into structured meaningful themes, these are deductive and inductive analysis. Deductive analysis, also known as top-down processing, begins with a hypothesis which is then tested, by filtering data into an existing theory or model. Whereas, inductive analysis allows the model or theory to develop directly from the data, and is usually utilised within interpretive and exploratory research (Hesse and Leavy, 2006).

Deductive analysis has been used within approaches such as post-positivism, where the investigator aims to build evidence to support a pre-existing theory. This method relies on deductive logic to provide evidence to confirm or refute theory, although not in absolute terms. Inductive analysis has also been utilised within several different approaches, including the well-known grounded theory, where theory is built from the raw data in a bottom up process. There are three main purposes for using inductive analysis: -

- Condense extensive and varied raw data into brief summary format
- Establish clear links between the research objectives and the summary of findings
- To develop a model or theory about the underlying structure, which are evident in the underlying data

(Thomas, 2006)

The primary purpose of inductive analysis is to allow findings to emerge from the frequent dominant themes inherent in the raw data, without key themes being obscured, misinterpreted, or left invisible due to preconceptions of the data caused by a preconceived theory.

The inductive analysis technique has been used in a variety of sports psychology studies (Hanton and Jones, 1999; Harwood, 1997; Scanlan et al, 1989a, 1989b), and has previously been employed to investigate players' perceptions of sports equipment (Barrass et al, 2008; Davies et al, 2003; Roberts et al, 2001), therefore this method was used in this investigation.

The first stage in the analysis procedure was to transcribe verbatim the recorded sessions and to become familiar with the content. Once familiarity with the data was gained, it was organised into structured meaningful themes by comparing and contrasting each quote with all other quotes; these were then clustered around underlying uniformities (Glazer and Strauss, 1967; Patton, 1990) and became the emergent base themes. This process was conducted using the software package NVIVO 7, which assists in grouping together similar quotes, allowing different categories to be formed and linked together, producing base themes. The base themes that shared a common subject were then grouped together to form lower order sub-themes. Within this process, alternative classification schemes of the same base themes were created; all possible classifications were formed and refined by removing redundant ones. A classification was considered to be redundant if all base themes could be re-coded into another alternative dimension (Roberts et al. 2001). As in previous studies the final structure was tested for completeness using a number of checks, leaving as few unassignable themes as possible. Any remaining quotes were disregarded if indistinguishable or retained if important (Scanlan et al, 1989b), this process was then repeated until it was not possible to further group the different categories together. According to Guba (1978) the final structure should be inclusive of the data and information that exists, therefore if the structure does not appear to sufficiently cover the facets of the problem it is probably incomplete

(Guba, 1978). The results were validated through investigator triangulation to ensure the correct grouping of quotes and base themes, reducing possible bias and increasing validity (Scanlan *et al,* 1989b).

2.2.6 Validation process

Further validation of the results was conducted through four individual interviews which completed the methodological triangulation. Individual interviews were chosen as the third method due to the interactivity between the participant and interviewer allowing for a greater understanding to be gained, and to compensate for any possible group affects within the co-discovery and focus group data collections. The interviews were conducted whilst participants used the pads in a similar manner to the practical test for the focus groups. The cricketers faced between 10 and 15 balls per pad, running a minimum of 6 runs, and padding different deliveries away to allow for a full assessment of the PPE. A bowling machine (Bola) was used to deliver the ball at 50mph representing an average spin delivery. Four different pads (P1, P2, P4, and P5, illustrated in Figure 2.2) were used by each participant, covering the range of pads available on the market. Prior to testing each pad, the participants were asked for their initial assessment of the equipment. Throughout the use of the pad, feedback was recorded using lapel microphones, and a final evaluation was gathered post use. This method was then repeated for all pads. The data collected was transcribed and analysed through a deductive process, where quotes were grouped into the themes that emerged from the inductive analysis of the focus group data. By utilising a deductive approach, the applicability of the model developed through the inductive analysis process previously outlined was assessed. If no new themes emerged and all quotes could be coded into the previously developed structure, then a data saturation point was deemed to have been reached.

2.2.7 Structured Relationship Modelling

The data collected was then analysed through the use of a technique called structured relationship modelling, developed by Roberts *et al* (2001). Quotes highlighting the interaction of different factors influencing the users' perceived comfort were used to link different themes and dimensions, allowing for further understanding of how different aspects of the pad design interact to determine perceived comfort.

2.3 The general dimensions of comfort for cricket leg guards

The aim of this first stage of testing was to identify the components influencing players' perceptions of comfort of PPE within cricket. From the initial assessment and analysis of the data collected, six main themes emerged: -

1. Aesthetics
2. Fit
3. Protection
4. Sensorial Comfort
5. Thermal Comfort
6. Weight

The tree structures produced from the raw data are illustrated in Figure 2.3 to Figure 2.13; with Figure 2.3 illustrating the general dimensions and higher order sub-themes, and Figures 2.4 to 2.13 demonstrating the formulation of each sub-theme from original quotes obtained in the left column to higher-order sub-themes and general dimensions on the right. The emergent themes are discussed in more detail in the following sections, demonstrating the inductive analysis process used to develop the model (black) and quotes from the interviews fitted to the model through the deductive process used to validate the results (red).

2.3.1 Aesthetics

The 'Aesthetics' dimension (Figure 2.4) emerged from the three sub-themes of 'Look of the pad', 'Self image' and 'Shape'. A player's initial impressions of a pad are largely determined by the appearance and this can influence their preferences.

"They could be the best pad on the table, but I would sooner go for the better looking pad"

"[I'd rank] these 4th just purely because they don't look like a cricket pad."

The appearance of a pad was found to influence comfort in a psychological manner due to the stereotypes and traditions of the sport. This was encompassed by the base-theme 'Style of the pad' and, generally, players described a preference for a more traditional looking pad.

"More traditional [design] than futuristic, that's the way I like pads."

"These rank lower because of looks. They are a good pad...they are light, but the looks for me, they just don't look like a cricket pad."

"I like the idea of these and they are a good pad but again, personal preference, I like the old school looking pads which a lot of players do, the traditional type."

Although these examples show that the majority of players prefer a traditional looking pad there is also the suggestion that as technology becomes increasingly important, change is imminent and, over time, objections to the look of modern pads could be overcome.

"'Does it look good?' will die out when people realise that, to increase performance you have to go with modern looking pads."

"In the end futuristic pads will become more popular... but at the moment people want to stick to what they are used to"

"Because of how light they are and how well they hug your leg and how good they feel when you are running...you will have to compromise [on looks] a bit I suppose."

These more positive comments suggest that modern designs will become more popular, but it will be a gradual change. Currently, for a pad to be deemed acceptable, a balance between technological advancement and traditional appearance needs to be maintained.

The appearance of a pad can determine a cricketer's willingness to use the pad and influence how comfortable they will feel. Due to peer pressure, pad appearance can affect self-consciousness and consequently the user's comfort. Therefore 'Self-Image' is the final sub-theme of 'Aesthetics'.

> *"They are quite comfortable though you* just *look like you have fat legs in them"*

> *"You would get absolutely ripped for them as look at them; I definitely wouldn't wear these at club level"*

> *"If you turn up on a Saturday wearing them you would just get annihilated, it wouldn't be worth it, which is probably why most of the county players haven't taken this style of pads on."*

2.3.2 *Weight*

The dimension 'Weight', illustrated in Figure 2.5, includes the users' perceptions of weight of different cricket pads and its influence on comfort. It incorporates two sub-themes –'Heavy' and 'Light'. Increased weight was found to cause feelings of clumsiness and made the pads feel cumbersome to wear.

> *"They seem heavier and awkward."*

> *"Looks wise these look good, [but] they are a bit heavy for me"*

> *"They aren't as comfortable as these, as they are quite a lot heavier"*

Feelings of a positive nature emerged when the pads felt light and this was seen to be beneficial to the perceived comfort.

> *"Because they were so light it felt good,"*

> *"Just because they were so light, it feels like you haven't really got anything on your legs"*

> *"The weight is the key issue; these have got it about right, as they have a good light weight and balance."*

2.3.3 Fit

'Fit' emerged as the dimension with the most sub-themes contributing to it (Figure 2.6 to 2.10). It incorporated 'Awareness', 'Customisation', 'Flexibility', 'Movement', 'Shape to the body', 'Size', and 'Strap design'. The cricketers reported becoming increasingly aware of the presence of the pads if they moved whilst running, which is clearly undesirable.

> *"When I was running, they turned right to the side, maybe I had them too loose, but I felt the straps would cut in"*

> *"When I was running, they went completely round the side, and when I was batting… I had to keep adjusting them"*

> *"If I am aware of my pads, it's a discomfort…and with any sport you have to be 100% comfortable with your equipment … as all you should be thinking about is hitting the ball nothing else"*

Although players commented on their dislike of the pads moving, they appeared to derive confidence from the feel of wearing pads.

> *"When you are batting you like to feel something there, it's good for your confidence… Also that's what you [have] felt all your life"*

> *"I am not confident in them at all because you feel like you are going for the ball with just your bare leg"*

The players highlighted a need for the pads to be adjustable and for there to be an opportunity to personalise the pads to their needs. These themes were grouped together within 'Customisation'.

> *"I am a fan of the movable knee cushion…so if you have Velcro, where you can actually push the knee pad up, then you can actually get the padding on the knee cap where you need it"*

"Players of different shape can break them in more, so if I am a bit taller I can wear them higher, if I am smaller I would break them in at the bottom, whereas with these if you were taller you would be in trouble,"

"Its just little tinkering that [can] make a big difference. You like to adjust these things individually. "

Flexibility was also found to be an important aspect affecting perceived comfort, due to the players dislike for stiff pads, which do not flex around the knee when moving.

"My only issue with those is they are absolutely rigid"

"They have one fault; they don't bend at the knee"

"There was more flexibility around the knees, meaning you could run and turn properly"

"Very rigid, almost dig into you round the side, on the inner calf and more so on the inside of ankle, which is where I've got the biggest issue."

As well as flexibility, the influence of the pad on movement can be severely detrimental to comfort as well as performance. Influences on movement include effects on motion and technique.

"I've not tried these but they are both straight, whereas some of the others bend to your leg a bit more, and that means they can get in the way so you have to play round it."

"Well the width of them will be a problem, in terms of being able to bring your bat through"

"You want good coverage of the pad, but you don't want to feel you can not move properly"

"These are good, nothings getting in your way on the knee roll or top flap, felt good,"

The way in which the pads shape to the body, in terms of wrapping around the leg and moulding to the individual, both before and after breaking the pads in, is seen to influence the perceived comfort of the pads.

> *"They felt like a proper pad, they went round my leg, very comfortable... you can break them in, so they contour to your leg,"*

> *"I like the way these are, they look like they are going to just wrap around like a cocoon which is the way forward"*

> *"I prefer pads that are shaped round my leg whereas these stick out quite a lot"*

> *"It's rare you get a pad that wraps 180 degrees around the leg... that's a plus point"*

Players of different sizes tend to use the same pads, resulting in pads which can be too wide for the individual, too short for them or just generally perceived as too small.

> *"These pads only just come over my knee, I would want these to come much higher up the leg."*

> *"These pads are just too short for me."*

> *"I just feel I would need a bigger size than this, do they do an XL?"*

The final sub-theme of 'Fit' was strap design and included quotes regarding the length and width of straps, adjustability, number of straps, the way in which they are fastened, the padding on the straps and the way they dig into the skin.

> *"Players strap pads differently, some do them tighter than others"*

> *"These days we get wider padded straps whereas on the old ones there are just 3 of these thinner ones, so they cut in."*

> *"They had buckles that went round the legs. We had to strap them up and buckle them in. Obviously Velcro is easier to put on and feels comfortable as well."*

"I don't like it when they make the straps too long, so you have to fold them over a little bit; I don't know why they make them that long,"

"I have had problems with straps behind my knee with certain pads,"

2.3.4 Protection

The level of protection was found to influence a player's willingness to use the pads, their confidence and overall satisfaction, which ultimately influences their perceived comfort (Figure 2.11). The 'Amount of Padding' and 'Weaknesses' within the pad are sub-themes contributing to the general theme of 'Protection'. Within these sub-themes the pad's thickness, amount that the leg is exposed to the ball, weaknesses within the knee roll and perceived level of protection are some of the contributing base themes.

"I am not going to use those; they look like they could break your leg, that is thin"

"When I used these pads [I] thought there was a lot of padding in them, so if you get hit it won't hurt,"

"They were a bit over padded, stopping you being able to move properly"

"Compared to my pads they look a bit flimsy… if I got hit on the leg I wouldn't be 100% confident"

2.3.5 Sensorial

'Sensorial' comfort, illustrated in Figure 2.12, includes the sub-themes of 'Material tactile feel', 'Smell', and 'Sound', and can be seen to influence the sensations of the wearer as well as umpiring decisions, and pleasantness of using the equipment.

"Sweating in the pads is fine, until they get old and start stinking"

"The material for these is quite hard, so if the ball was to skim off it would sound like an inside edge or something"

"I like the feel of leather pads,"

2.3.6 Thermal

The two sub-themes incorporated within the 'Thermal' theme, illustrated within Figure 2.13, are 'Sweat', with a base theme of 'Pad Rash' and 'Breathability'. These sub-themes illustrate the user's dislike for increased sweat rates and the discomfort caused by pads prior to batting.

> *"Netting material helps, as there is a space between it [the pad] and the cotton of the trousers, which is what causes you to sweat."*

> *"Pad rash, that's when you are waiting to bat for ages, because you are not moving around you sweat, if you keep moving round you are ok,"*

> *"I think it could be to do with the breathability of the pad"*

2.4 Structured relationship model results

Relationship modelling was used to identify links between different themes through analysis of the data collected. There were 13 links identified within the data as shown in Figure 2.14. These links represent the participants' perceived influence of one theme on another and the relationship between them. For example, the sub-theme 'Amount of padding' was found to be associated with three other themes through various quotes:

Movement – Amount of padding

> *"Sometimes they can be too bulky and difficult to run in."*

> *"They were a bit over padded stopping you being able to move properly"*

> *"Others can be over padded and you are not able to move in them."*

Size – Amount of padding

> *"A lot of padding so it's really comfortable, but they look quite big, they look bulky"*

Flexibility – Amount of padding

> *"Flexibility is key, but you've got to have the padding as well."*

> *"One thing I always want is flexibility, but with the padding,"*

These examples demonstrate how the perceived increase in the amount of padding can affect the players' perceptions of size and flexibility of the pad as well as their ability to move whilst using the equipment, which will ultimately influence their comfort and performance.

These relationships highlight the users' perception of each category and its relationship with other sub-components, but it does not show the relative importance of each characteristic. Further knowledge is needed to be able to fully understand the relationships between dimensions and the resultant effect each theme has on overall comfort, allowing designers to focus on factors that will be most beneficial in terms of user comfort and satisfaction.

2.5 Comparison of two sports

The second stage of this study was to assess the appropriateness of having one comfort model representing different items of PPE, as can be found within the literature. For this analysis a comfort model was developed for a taekwondo hogu, for comparison with the cricket model previously described.

2.5.1 Taekwondo Methodology

A similar method to the one previously described for the cricket study was followed for taekwondo to investigate the factors influencing perceived comfort of a chest guard (hogu). The aim of this was to investigate whether factors perceived to be important in determining comfort are specific to the individual piece of equipment or if there is a consistent perception of factors affecting comfort across a range of protective garments for sport.

Due to the inherent differences between the two sports, the methodology had to be altered accordingly. Taekwondo is an individual sport, so the individual interviews were used as the predominant source of information rather than the co-discovery and focus group sessions. For the four individual interviews, the fighters wore 4 different chest guards which were chosen to represent the market (illustrated in Figure 2.15), for 3 two minute rounds each. Two rounds were deemed suitable as it reflected a competition bout and gave the fighters opportunity to fully evaluate the protective equipment when both attacking and defending. During the interview process an initial evaluation of the pad was collected immediately after putting the hogu on, followed by an ongoing evaluation between each round and finally a summary prior to changing hogu. This was repeated for all four hogus, which were randomly ordered to prevent any order effects. All interviews were recorded using a lapel microphone and stored for further evaluation.

Data analysis followed the procedure previously outlined in section 2.2.5. Two focus groups were conducted to validate the model produced from the interview data. Each focus group involved six fighters and followed a similar structure as used in the cricket testing.

2.5.2 Taekwondo tree structure results

As with cricket, six general dimensions were identified; these were 'Aesthetics', 'Fit', 'Weight', 'Thermal', 'Protection' and 'Sensorial' as shown in Figure 2.16. Within each of these general dimensions several contributory factors were identified as being influential to the users' perceived comfort (Figure 2.16 to 2.25).

The appearance of the pad was again found to influence users' perceived comfort due to players likes or dislikes of the look of the hogu, leading to feelings of self awareness and ultimately concern over self image.

> *"These are the ones most people wear….so they look pretty similar, so if you come in with something like the others they don't look as good, and you would just look like an idiot"*

Associated with the pads' appearance was the brand of the hogu, as different users demonstrated a preference towards certain manufacturers due to brand image and specific design features associated with their preferred make.

> *"I always go with these pads as I like the look of them, they always look better than other makes."*

Fit was another key factor identified as affecting perceived comfort, with feelings of discomfort being associated with larger, bulky pads which were perceived to be less flexible preventing the hogu shaping to the body.

> *"I would rather wear a thinner one (hogu) and [a] more comfortable one as it is too big and thick when you are wearing it."*

Feelings of restriction caused by the hogu limiting movement were also perceived as a major source of discomfort. In general, awareness of the pad moving around whilst fighting and an inability to adjust the pad to the user's preferred position due to non elastic material within the straps, were both considered undesirable.

> *"With the other one you don't notice that much that you are wearing one, whereas, with this its like right out there and you know you are wearing one when you are fighting and its just not comfortable because after every attack you have to re-adjust it."*

> *"This one kept on coming loose and didn't feel secure, that's why I prefer the stringed ones to these new Velcro ones."*

The hogu is designed as a piece of protective equipment and users described the level of protection as another factor contributing to their overall comfort. Their perception of protection provided by the hogu appeared to be determined by the amount of padding and the degree to which they felt exposed by uncovered areas.

> *"This pad has no padding so you just don't feel protected, and you worry about getting hit as you know it will hurt"*

> *"When I am kicking it moves up and if it's up there your hips are open for a kick"*

Within the comfort model, the interaction between the hogu and the five senses were encapsulated within the general dimension of sensorial comfort, illustrating the importance of sound and material tactile feel in terms of perceived comfort. A source of discomfort was associated with the sound the pad made when struck due to it being perceived as a source of information for the judge when fighting.

> *"If someone kicks you in the back they don't usually score it but they might do if it makes a noise."*

Material tactile feel was associated with the interaction between the skin and material of the pad, with feelings of discomfort being attributed to rough and scratchy material, particularly around the neck.

> *"The only thing I think is wrong with this pad is around the collar, as it's a bit rough and scratchy so it's uncomfortable."*

The final two general dimensions were 'Thermal' and 'Weight'. A preference was shown for pads which were perceived to allow greater heat dissipation and had increased breathability, as well as being light weight.

> *"This pad gets really hot as no air can escape so you just get hotter and hotter"*

> *"These pads are really light which makes it much better to move in and so more comfortable."*

2.5.3 Taekwondo structured relationship model

Within the players responses were perceived links between different general dimensions identified, as with the cricket results. Twelve inter dimension links were identified within the model and these are shown in Figure 2.26. An example of these links is between thermal and sensorial, demonstrating that if the hogu allows less heat to be dissipated a greater amount of water will be collected within the garment having a negative affect on the material tactile feel.

"Because these pads get so hot you get really itchy as you sweat loads"

2.5.4 Comparison of results

The comfort models for taekwondo and cricket are very similar particularly at the general dimension level. Slight differences within the higher order sub-themes can be seen, but after this level the differences do become more apparent due to the different uses of the equipment, as illustrated in Figure 2.27. One reason for these subtle differences within the higher order sub-themes is the use of different terminology; for example, taekwondo players refer to the way in which the pad can be altered to suit the user as adjustability, compared to cricketers who describe this as customisability. The differences within the lower order sub-themes appear to be due to the inherent differences between the sports; for example, within the taekwondo model, protection incorporates coverage of the hips and protection of the back which were not identified within the cricket comfort model due to the pads being used to protect different areas of the body and within different situations, therefore protecting against different risks of injury.

2.6 Discussion

The aim of this work was to identify factors influencing the comfort of different sports PPE and the way they are interrelated. Current literature has focused on symptoms of discomfort rather than causes, limiting the use of the findings in product development to optimise user comfort. Through the use of subjective methods, this study has identified several factors influencing the perceived comfort of PPE. It suggests that perceived comfort can be influenced due to the appearance and the initial interaction between the user and the equipment. This initial interaction can include picking the pad up, bending it and hitting it, as well as analysing how the pad looks. This initial assessment then combines with the wearer's experience whilst using the pad to produce their overall perceived comfort.

From the analysis, a great deal of similarity was found between the two sports of cricket and taekwondo, with the same six general dimensions emerging as influencing users' perceived comfort. The attributes identified within both sports are believed to interact and influence one another to determine the users' perceived comfort, as demonstrated by the structured relationship models. As with the tree structures, it was found that there is a great deal of similarity between the two sports, as the players identified very similar inter-dimension links, with the links of both models being either positively or negatively correlated. One example of a positive relationship within both models is between the amount of padding and weight of the pad, as it emerged that as the amount of padding increased so did the weight.

Within the relationship models, negatively related links were also highlighted, where increasing one component was perceived to decrease another. An example of this is between material tactile feel and sweat, where increased sweat decreases tactile feel of the material. Therefore, if sweat production is decreased by improving thermal comfort, material tactile feel will improve. Another example of this is between weight and movement, where a decrease in weight was found to increase player movement. This was highlighted through quotes such as:

> *"Also when I was running in them they seemed dead light, and obviously the less weight you are carrying when you are out there the better, as it means it is a lot easier to move"* (cricket)

> *"Because of the weight of the pad you can feel it on the top of your leg making it difficult to kick"* (taekwondo)

Although these results do demonstrate the interaction between dimensions, the data does not reveal the importance of the different dimensions nor the magnitude of their influence on perceived comfort. Such knowledge would be beneficial in the product development process as it would allow the designer to focus on the more significant features of PPE. Therefore the emergence of these relationships warranted further study focusing on how the different factors affecting perceived comfort interact and the relative importance of each dimension.

Chapter 3

Development of a hierarchical model and model validation

The comfort models, developed in Chapter 2 identified specific design features that affect comfort and the way in which they are inter-related. The identification of these characteristics has furthered knowledge regarding player comfort and in turn end-user satisfaction. However, further information was required to direct the design process regarding the relative contribution of each dimension in determining perceived comfort. Therefore this chapter aimed to develop the comfort model documented in Chapter 2 into a structured hierarchy, suitable for being used as a predictive tool for both cricket leg guard and taekwondo hogu comfort, through the use of a psychometric instrument.

The Analytical Hierarchy Process (AHP) was identified as an appropriate method for determining the perceived importance of each general dimension. This method was adopted due to its ability to decompose a complex multi-criteria problem such as comfort, into a hierarchy (Saaty, 1980) and has the advantage of allowing participants to assign different magnitudes of opinion to each dimension. Saaty evolved the AHP method to allow decision makers to represent complex interactions of multi-factor constructs in a hierarchy (Chen, 2006; Hsu *et al*, 2008; Montaza and Behbahani, 2007). Another advantage of AHP is the incorporation of a consistency check, with the capacity to identify inconsistent responses, therefore, increasing the reliability and validity of the results. This method has been widely accepted across multiple disciplines, including business management, textiles and manufacturing (Frazelle, 1985; Golden *et al*,, 1989; Mohanty and Venkataraman, 1993; Saaty, 1979; Wabalickis, 1988). These studies have demonstrated its appropriateness in assessing both tangible and non-tangible factors, especially where the subjective judgments of different individuals constitute an important part of the decision process, again demonstrating its suitability for use within this study.

This chapter is split into three main sections. The first section focuses on the development of an online questionnaire for the cricket leg guard and assessment of the results. The second section compares the results for the cricket leg guard and taekwondo hogu and the final section assess the validity and accuracy of the two models.

3.1 Questionnaire design for cricket

An online questionnaire (Appendix 2) was deemed as the most suitable method of collecting data for the AHP, due to it being easily accessible to large numbers of people, allowing for a large sample size to be generated with minimal cost and ease of distribution to a variety of geographical areas. The online questionnaire was distributed to twenty cricket clubs, resulting in 108 completed questionnaires being submitted. The 108 respondents had a mean age of 23.7 years; there were 80 male respondents and 28 female, with 66 of them playing at club level and 42 playing county level or higher. The AHP was used to identify the perceived importance of each general dimension in determining comfort. The online questionnaire developed was split into two main sections, with the initial part aimed at developing the comfort model into a hierarchy, followed by a second section which was used to gather additional information on players' perceptions of current PPE.

3.1.1 Development of a hierarchy of importance for cricket

The known method of Analytical Hierarchy Process (AHP) was used to calculate a relative importance weighting for each general dimension, from the responses given on a sliding scale. Pair-wise comparisons of each combination of general dimensions were completed in accordance with Saaty's (1980) AHP, allowing results from the initial data collection and analysis process to be represented in a hierarchical structure.

Participants were asked to indicate how much more important one general dimension was than another using a relative importance scale. The scale used to compare 'Fit' and 'Weight' is illustrated in Figure 3.1 as an example. Using these judgements a prioritized rank order was developed through the composition of an n x n pair-wise comparison matrix for each respondent, where n is the number of general dimensions. In Equation

3.1, C_1, C_2 ... C_n denote the elements (in this case the general dimensions), while a_{ij} represents a quantified judgment on each pair of elements C_i and C_j. If two elements C_i and C_j are judged of equal importance, a_{ij} = a_{ji} = 1. If C_i is judged to be 'slightly more important', 'more important' or 'much more important', a_{ij} takes a value of 3, 5 or 7 respectively and a_{ji} = 1/ a_{ij}. Alternatively if C_j is judged to have a greater importance, then a_{ij} takes the value of 1/3, 1/5 or 1/7, depending on the magnitude of importance, and again a_{ji} = 1/ a_{ij}. An example of a completed matrix is shown in Table 3.1.

$$A = [a_{ij}] = \begin{array}{c} \\ \mathbf{C_1} \\ \mathbf{C_2} \\ \vdots \\ \mathbf{C_n} \end{array} \begin{array}{c} \begin{array}{cccc} \mathbf{C_1} & \mathbf{C_2} & \cdots & \mathbf{C_n} \end{array} \\ \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \end{array} \qquad (3.1)$$

	Weight	Thermal	Protection	Fit	Sensorial	Aesthetics
Weight	1	3	3	3	7	7
Thermal	0.33	1	0.14	0.33	3	7
Protection	0.33	7	1	3	3	7
Fit	0.33	3	0.33	1	3	7
Sensorial	0.14	0.33	0.33	0.33	1	3
Aesthetics	0.14	0.14	0.14	0.14	0.33	1

Table 3. 1: An example of a completed AHP matrix for subject 1

After the pair-wise comparison matrices were formed for all respondents, vectors of weights (*w*) were computed on the basis of Satty's eigenvector procedure. The weights were calculated through a two step process; initially the pair-wise comparison matrix was normalised through equation 3.2, and then the weights were calculated through equation 3.3.

$$a^*_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \qquad (3.2)$$

$$w_i = \frac{\sum_{j=1}^{n} a*_{ij}}{n} \qquad (3.3)$$

The vector *w*, contains a weighting for each element (C_i), where the $\sum_{i=1}^{n} w_i = 1$, and the values of w_i are an indication, in this case, of the relative importance of each comfort dimension for that particular respondent. There is a common relationship between the vector weights, *w*, and the pair-wise comparison matrix, demonstrated within equation 3.4.

$$Aw = \lambda_{max} w \qquad (3.4)$$

Using λ_{max}, the data can be screened through the development of a consistency ratio (*CR*) of the estimated vector. The *CR* can be calculated once the consistency index *(CI)* for each matrix of order *n* has been determined through equation 3.5.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (3.5)$$

Then *CR* is calculated through equation 3.6

$$CR = \frac{CI}{RI} \qquad (3.6)$$

RI is the random consistency index obtained from a randomly generated pair-wise comparison matrix and is a set value dependent on *n*, which is the number of general dimensions identified within the first stage of testing. An *RI* value of 1.24 was used in accordance with Saaty (1980). The *CR* can vary between 0 and 1 and is a measure of the consistency of an individual subject's responses, with a higher number indicating a greater degree of inconsistency in their data. Typically, a threshold value is selected and the data from subjects whose *CR* exceeds this value are removed from the analysis. For this study, a maximum *CR* of 0.2 (20%) was utilised instead of 0.1 (10%) to make the results more inclusive rather than exclusive. As a result, 8 sets of responses were removed from the analysis.

The mean weighting for each dimension for the 100 accepted responses from the 108 respondents was calculated and is shown in Figure 3.2. Within the 100 accepted responses, the mean inconsistency was 0.126 ± 0.034 (12.6% ± 3.4%). The results indicate that 'Fit' (30.9% ±9.8%) was perceived to be the most important factor affecting comfort, followed by 'Protection' (24.2% ±9.8%), 'Weight' (16.8% ±7.2%), 'Thermal' (11.97 ±6.88%), 'Sensorial' (8.32% ±5.1%) and then 'Aesthetics' (7.78% ±5.9%) (Figure 3.2A).

3.1.2 Statistical analysis of cricketers' responses

The AHP results have allowed a perceived weighting to be assigned to each dimension, however, the significance of the differences in perceived importance has not been determined. Therefore, three statistical methods were utilised to help interpret the results, and determine if these differences were significant. The three methods used were- Bootstrapping, t-test and Cluster analysis. The initial analysis of the combined AHP results from all respondents was completed to determine if there were any significant differences in perceived relative importance of the general dimensions. Within this stage of analysis it was deemed that a standard ANOVA was not suitable as the results were not totally independent of one another, therefore a bootstrapping technique was utilised to obtain a 95% BC_a (biased corrected accelerated) confidence interval, enabling any significant differences between dimensions to be analysed. This technique involves resampling - with replacement – of a given sample, where sub-samples are withdrawn from the original data and replaced by replicating random other samples. For example, from a sample of 100 responses, a new sub-sample may consist of 90 of their scores with 10 replicated results used to produce a new sample of 100. The mean weighting for this new sample is calculated before the procedure is repeated 10,000 times. From this, the 95% BC_a is calculated.

This method allowed a valid statistical result even though the standard statistical assumption of normality did not hold. Bootstrapping was regarded as more valid and reliable than other possible methods such as jackknife and cross validation as, rather than deleting results, bootstrapping utilises a constant resampling with replacement method to develop an empirical distribution for a given sample statistic that provides the framework for computing the averages, standard errors, and confidence intervals (Efron, 1979; Efron and Tibshirani, 1993). Because the sampling or resampling in the bootstrap method takes place, the combinations of samples are limitless and are driven by random number generators from Monte Carlo. Weightings were deemed significantly different if no overlap occurred between dimensions when the 95% confidence intervals were evaluated.

The bootstrap results are shown in Table 3.2 and indicate a clear difference between all dimensions except 'Aesthetics' and 'Sensorial' whose intervals were 6.84 to 9.20% and 7.49 to 9.49% respectively (Figure 3.3). The substantial amount of overlap between the two dimensions indicates that there is no significant difference in perceived importance.

	Lower limit (%)	Upper limit (%)
Weight	15.5	18.3
Thermal	10.7	13.4
Protection	22.3	26.2
Fit	29.0	32.8
Sensorial	7.5	9.5
Aesthetics	6.8	9.2

Table 3. 2: 95% confidence ranges for the cricket leg guard weightings generated from the bootstrap analysis

Once this analysis had been completed, a t-test was used to determine if there were any significant differences between the demographical groups of male/female (*N*= 72 and 28) and amateur/professionals (*N*= 66 and 34). For this analysis, players were deemed to be professional if playing at County second team level or above, as during the summer months these players train on a full time basis, whereas the amateur sub-category incorporated university and local club players. The results are shown in figure 3.2b) and c). A t-test indicated no significant differences between the different groups of players, demonstrating a consistent trend between both sexes (p=0.455) and across all levels of performer (p=0.390).

Although no significant differences between these categories of players were found, the large standard deviation within the dimensions did suggest some differences of opinion between respondents. To further analyse these differences, the statistical method of clustering was used to determine if there were any sub-groups within the respondents regarding the relative importance of the different dimensions. Hierarchical clustering was used to study the Euclidean distance to the furthest neighbour. The aim of this analysis was to identify any sub-groups of respondents within the data which can not be identified through demographical differences. This grouping of data is accomplished through the maximisation of between group variance and the minimisation of within group variance. It was found that the respondents can be split into two distinct groups predominantly determined by the perceived importance of 'Protection' and 'Fit', as shown in Figure 3.4. Subjects in Group One (Figure 3.5) placed a higher emphasis on 'Protection' (N=34), whereas those in Group Two (Figure 3.6) perceived 'Fit' to be of greater importance when determining comfort (N=56). Ten subjects did not fit into either group. It was not possible however to identify a demographical characteristic that separated the two groups.

3.1.3 Additional information on cricket leg guards

The second section of the questionnaire focused on gathering additional information regarding players' preferences in terms of protection, aesthetics, strap and knee roll design. These areas were focused on due to the number of references made regarding these specific design features within the interview process described in Chapter 2, and were deemed to be suitable for further analysis through an online questionnaire. The initial question focused on perceived protection and aimed to identify where the cricketers would prefer the greatest amount of protection. This was done by dividing a pad into eight zones, as illustrated within Figure 3.7; the respondents were then asked to rank each area in terms of protection from 1 to 8 with 1 being where they would like the greatest amount of protection and 8 being the least. In the analysis of this data, 90 out of the 108 responses were used, as 18 respondents failed to complete this section correctly, therefore, their results were excluded. Figure 3.8 illustrates the rank sum for each of the 8 zones for all 90 accepted responses, with a low rank sum indicating a greater need for protection. The results were then analysed using Friedman's test, to determine whether there were any significant differences in areas of perceived protection. Friedman's T statistics was calculated from the number of subjects, N, the number of samples, k, and the rank sums, R_j, using Equation 3.7.

$$T = \left(\frac{12}{Nk(k+1)} \sum_{i=1}^{k} R_j^{\,2} \right) - 3N(k+1) \qquad (3.7)$$

The Friedman test statistic, T=186.8 is greater than the critical value from the chi-square distribution of 18.5 (at a significance level of 0.01), indicating that players perceived some areas of the pad to require more protection than others. Fisher's LSD_{rank} (least significant difference) was then used to identify which areas of the pads were perceived to need the highest levels of protection. Fishers LSD_{rank} was calculated through the use of $t_{\alpha/2,\infty}$ which is equal to 1.96 for α = 0.05, using Equation 3.8.

$$LSD_{rank} = t_{\alpha/2,\infty} \sqrt{\frac{Nk(k+1)}{6}} \qquad (3.8)$$

It was calculated that, for there to be a significant difference ($p<0.05$), the rank sums needed to differ by more than 63.3. From the results, it is apparent that the centre of the knee and the shin area (Zones 3 and 6) were perceived to need significantly more protection than the rest of the pad with rank sums of 225 and 239 respectively. After these two areas, players perceived the outside of the knee and lower leg (Zones 4 and 7) to require the most protection, with the inner area of the knee (460.5), lower leg (516.5), top (473.5) and bottom (500.5) of the pad needing significantly less protection (Zones 1, 2, 5 and 8).

The next question focused on the aesthetics of the pads and required the respondents to evaluate four different pads (P1, P2, P4 and P5 as depicted in Figure 2.2) in terms of the appearance of the entire pad, the section above the knee, the knee and the shin (Figure 3.9). The four pads illustrated within this section were chosen as a representative sample of the current market, varying from the more traditional pads to the modern looking pads as depicted in Figure 3.9. The results were analysed by assigning a score of 2, 1, 0, -1 and -2 to represent 'very good', 'good', 'ok', 'poor' and 'very poor' respectively. A one way ANOVA was used to determine if differences in scores were significant ($p<0.05$). The results illustrated that respondents preferred the overall shape of P1 and P4 (Figure 3.10) with average ratings of 1.28 and 1.22 respectively, which were significantly higher ($p<0.05$) than P5 (-0.08). P2 was perceived to have the worst overall shape with an average score of -1. In terms of the area above the knee, P1 and P4 were again identified as being significantly ($p<0.05$) more aesthetically pleasing than P5 (Figure 3.11) with average scores of 1.1 and 1.3 compared to 0.2 respectively, with P2 significantly less appealing than pads P1, P4 and P5 with an average score of -0.7. The same trend can also be seen for the knee (Figure 3.12) and shin (Figure 3.13).

The final two questions focused on strap design and whether players preferred pads to have a knee roll. The results illustrated that 93% of players prefer pads to have three straps rather than two (Figure 3.14), and 91% of respondents would prefer pads that have a knee roll (Figure 3.15).

3.1.4 Discussion Cricket results

The purpose of this study was to develop a greater understanding of end-user needs in terms of cricket leg guard comfort, by further developing the comfort model described in Chapter 2, through the addition of weightings for each general dimension reflecting perceived importance. In this study, 66% of players perceived fit as the most important factor; for the remaining 34% fit was the second most important factor behind protection. As well as fit, protection and weight were perceived to contribute significantly, with thermal, aesthetics and sensorial affecting their preference to a lesser extent.

Through the second section of the questionnaire, specific design features have been identified in terms of maximising end-user satisfaction. It was apparent that the end-user perceived the centre of the pad to need the most protection followed by the outside edge. A preference towards more traditional looking pads, which conformed to the standard shape that players are accustomed to, such as P1 and P4, was demonstrated over more modern leg guards. Typically, players also wanted pads to incorporate three straps and a knee roll into the design.

These findings suggest that, within the design process, maximising fit and protection should be focused on when designing cricket leg guards, with less emphasis on aesthetics, sensorial and thermal properties if necessary, in order to maximise end-user comfort. With regards to the aesthetics of the pad, there is an apparent discrepancy between the interview data presented in Chapter 2 and AHP results, demonstrating the benefit of incorporating different processes within the method. It can be concluded that, as the majority of pads still maintain traditional features, their appearance does not have a large impact on overall comfort. It is only when players are presented with a completely unique modern pad without the traditional features expected that aesthetics begin to have a considerable influence on comfort. These pads, however, are much less common. The initial interview process where pads were presented to the players ascertained their feelings on the full range of pads presented, whereas the questionnaire focused more on their perceptions of a typical pad, or the pads that they currently use, which for most players was still a traditional-style pad.

3.2 Questionnaire design for taekwondo

To determine if there is a need for separate comfort models for different items of PPE, or whether one model can represent all garments, a comparison between the cricket leg guard and taekwondo hogu results was conducted.

3.2.1 Questionnaire design taekwondo

The data collection and analysis process for taekwondo followed the same method as described in section 3.2 for part one of the questionnaire, allowing specific weightings of importance to be calculated for each dimension. The second section of the taekwondo questionnaire also focused on gathering extra information regarding protection, and strap design as with the cricket questionnaire.

The online questionnaire was distributed to twelve taekwondo clubs, resulting in 48 completed questionnaires being submitted. The 48 respondents had a mean age of 21.4 years; there were 31 male respondents and 17 female, with 38 of them competing at club level and 10 competing at county level or higher

3.2.2 Development of a hierarchy of importance for taekwondo

As with the cricket results in section 3.2, a hierarchy of importance was developed for the hogu comfort model. The analysis of the AHP results followed the same process using the statistical methods of bootstrapping, t-tests and cluster analysis. Within these results a mean weighting was ascertained for each of the six general dimensions from the 43 accepted respondents identifying 'Fit' (30.58% ±7.8%) as the most important factor affecting comfort, followed by 'Weight' (23.2% ±5.7%), 'Thermal' (16.14% ±8.5%), 'Protection' (15.18% ±7.2%), 'Aesthetics' (7.88% ±3.43%), and 'Sensorial' (6.59% ±3.02%) (Figure 3.16a). The combined results were then analysed through the use of the bootstrapping technique (Table 3.3), which revealed 'Fit' to be perceived as the most significantly important of the six dimensions (Figure 3.17). 'Weight' was also perceived as being significantly more important than 'Thermal', 'Protection', 'Aesthetics' and 'Sensorial', no clear difference was found between 'Thermal' and 'Protection' due to there being a large degree of overlap between the two 95% confidence ranges, but were found to be perceived as more important than 'Aesthetics' and 'Sensorial', between which little difference was found.

	Lower limit (%)	Upper limit (%)
Weight	21.58	25.01
Thermal	13.67	18.67
Protection	13.2	17.46
Fit	28.38	33.02
Sensorial	6.93	8.93
Aesthetics	5.77	7.57

Table 3. 3: 95% confidence ranges for the taekwondo hogu weightings generated from the bootstrap analysis

These results were also divided into demographical groups of male/female and novice/expert, with novices denoting people fighting at club level, whereas experts were national, regional and county representatives (Figure 3.16 B and C). The results for these different groups were compared using a t-test analysis, but no significant differences (p>0.05) between demographical groups emerged. To complete the analysis of these results, a cluster analysis was performed which identified two sub-groups that could not be separated by demographical differences. These two groups were determined by the relative importance they attributed to the two dimensions of 'Thermal' and 'Protection'. Sub-group one (Figure 3.18) assigned a greater importance to 'Thermal' compared to 'Protection', whereas sub-group two (Figure 3.19) perceived 'Protection' to be of greater importance. Eight subjects did not fit into either sub-group.

3.2.3 Additional information on taekwondo

The additional information on taekwondo hogus was assessed in a similar manner to the cricket leg guards except, the hogu was split into 6 zones rather than eight when assessing protection as illustrated in Figure 3.20, and the question regarding strap design focused on type of fastening system, asking:

Do you prefer Velcro or string fastening system?

The taekwondo questionnaire did not include the question regarding aesthetics, as the majority of hogus' only differ subtly in terms of their appearance. Finally, the question regarding knee rolls was omitted and replaced by a question asking:

Does the pad rub/ dig into your neck?

Within Section 2 of the taekwondo questionnaire, all 43 responses were accepted, and analysed in the same way as with the cricket results. It was found that the respondents perceived there to be a greater need for protection around the side of the body (Figure 3.21) with rank sums of 74 and 82 for the right and left side respectively (Zones 3 and 2). As the difference in rank sums between these two zones and the other four zones was greater than the LSD_{rank} of 34, the difference is significant ($p<0.05$). It was found that the front of the pad, which covers the chest and abdominals (Zone 4) was perceived to require the next greatest amount of protection, recording a rank sum of 286, followed by the back (Zone 2) which had a rank sum of 330.5 assigned to it. Finally, the areas at the top and bottom (Zones 1 and 6) of the hogu were perceived to require significantly less protection than the other 4 areas ($p<0.05$). This section of the questionnaire also revealed that 79% of respondents had a preference for string fastening hogus compared to 21% in favour of the Velcro fastening system (Figure 3.22). The final question revealed that 44% of respondents found that the pad rubbed and irritated the neck whilst fighting (Figure 3.23).

3.2.4 *Comparison of the AHP results for two sports.*

Within Chapter 2, it was identified that the comfort models for cricket and taekwondo were very similar; however, it was noticeable that there was a difference in the emphasis placed on each dimension between the sports. These differences were supported by the AHP results, with each sport attributing varying levels of importance to each general dimension. It was found that both sports place the highest emphasis on fit, but in cricket, protection is also of key importance whereas in taekwondo, weight was found to be more influential. In taekwondo, thermal properties of the hogu influence perceived comfort to a greater extent than in cricket, with it being comparable to protection in terms of importance. These differences could be attributed to the inherent differences within the two sports and the areas of the body the PPE are designed to protect. Taekwondo is a faster more physically demanding sport, where over-protection could affect the dynamics of the sport resulting in fewer knock outs. Cricket is more focused on minimal restriction of movement and maximal protection, preventing players having to retire due to injuries.

3.3 Model validation

Once the development of the hierarchical model was completed, it needed to be assessed in terms of suitability and accuracy. To determine if the model was representative of players' perceptions of comfort, it was evaluated as a predictive tool, to discover if the responses given regarding each dimension could be used to identify the most comfortable pad overall.

To analyse the accuracy of the hierarchical comfort model for both cricket and taekwondo four pads (P1-P4 for both sports illustrated in Figure 2.2 and 2.15) were assessed in terms of 'Fit', 'Weight', 'Protection', 'Thermal', 'Sensorial' and 'Aesthetics' for each sport, as well as overall comfort. For cricket, ten subjects were required to wear each leg guard for 24 deliveries (4 overs) running 12 runs and padding away a minimum of 3 deliveries. After each pad had been worn, the subjects assessed the pad using a continuous scale with regards to each dimension (Figure 3.24) as well as for its overall comfort. Each pad was assessed on the same set of scales, enabling the pads to be placed in a rank order; a rank of one was given to the most preferred pad for each dimension i.e. the best fitting, lightest, most protective, best heat balance, better looking and best feel. Each rank was then multiplied by the appropriate weighting calculated from the AHP process for that dimension. For example, if a pad was ranked 3rd in terms of fit, 3 was multiplied by 30.9% (for cricket). These scores were added together for each pad to give an overall score, with the lowest score representing the most comfortable pad. To assess the accuracy of the model, the rank order of pads produced from the comfort model weightings was compared to the rankings of overall comfort, with an exact match suggesting the model was accurate. For taekwondo, a similar method was utilised but the practical assessment involved the participants sparing with each pad for two rounds prior to assessment.

3.3.1 Model validation results

The results from the model validation testing indicated that the cricket model was accurate in predicting the correct order of preference in 80% of cases (8 out of 10), as illustrated within Table 3.4. The taekwondo model predicted the correct order of preference in 77.8% of cases (7 out of 9) (Table 3.5), once again suggesting that the model is appropriate and relatively accurate as was found with the cricket model.

Subject	Overall Comfort Rank P1	P2	P3	P4	Predicted Rank P1	P2	P3	P4
1	1	3	2	4	1	3	2	4
2	2	4	1	3	1	4	2	3
3	3	4	1	2	3	4	1	2
4	3	2	1	4	3	2	1	4
5	2	3	1	4	2	3	1	4
6	4	2	1	3	4	2	1	3
7	2	4	1	3	1	4	3	2
8	1	4	2	3	1	4	2	3
9	2	3	1	4	2	3	1	4
10	3	2	1	4	3	2	1	4

Table 3. 4: Comparison of actual and predicted rank order of perceived comfort for the cricket leg guard

Subject	Overall Comfort Rank P1	P2	P3	P4	Predicted Rank P1	P2	P3	P4
1	2	1	4	3	2	1	4	3
2	1	3	2	4	2	1	3	4
3	3	2	1	4	3	2	1	4
4	1	2	4	3	1	2	4	3
5	1	3	2	4	1	2	4	3
6	3	4	1	2	3	4	1	2
7	2	1	4	3	2	1	4	3
8	1	3	2	4	1	3	2	4
9	1	3	4	2	1	3	4	2

Table 3. 5: Comparison of actual and predicted rank order of perceived comfort for the taekwondo hogu

3.4 Summary

The aim of this work was to develop the comfort model documented in Chapter 2 into a structured hierarchy, suitable for being used as a predictive tool for both cricket leg guard and taekwondo hogu comfort. This was achieved through the use of the well documented technique of AHP, which was administered through an online questionnaire. The analysis of these results identified notable differences between the two sports regarding the relative importance of the six general dimensions identified within Chapter 2. A greater emphasis was placed on fit in terms of determining perceived comfort for both pieces of equipment. For cricket, other key factors included protection and weight, whereas for taekwondo weight and thermal properties were perceived to be more important when determining perceived comfort. These differences support the argument that a specific comfort model needs to be developed for each piece of equipment in order to maximise end-user comfort and in turn satisfaction.

The final stage was to test the accuracy and validity of the models. The models were used to predict the order of four different garments for both cricket and taekwondo in terms of perceived comfort. Both models were shown to be very accurate predicting the correct order in over 77% of cases for both the leg guards and hogu.

Chapter 4

The effect of cricket leg guards on batting kinematics and shot performance.

4.1 Introduction

The purpose of developing a hierarchical comfort model was to elicit the perceptions of the end-user and structure them into an appropriate representative model, detailing the relative importance of the factors that determine the players' comfort and in turn satisfaction with the end product. The next stage in the project was to develop objective tests that could be used to assess the subjective concept of comfort.

'Fit' was identified as the most influential factor within the comfort model by the majority of players. One sub-component of 'Fit', which was frequently discussed, was the effect leg guards have on players' movement, including both their ability to perform different shots and the speed or ease with which they can run. Generally, players perceived that pads limited their ability to perform the different movements required within a game of cricket depending on their design. Therefore, the following two chapters will detail the methods used to assess players' movement when playing different cricket shots and the effect of leg guards on running performance. This chapter aimed to determine the affect of cricket leg guards on batting kinematics in terms of physical restriction and shot performance for a variety of shots.

4.2 Effect of PPE on Fit and Range of Motion

The fit of a garment has been identified as one of the most influential components of comfort, both directly, in terms of size and shape relative to the wearer and indirectly through its influence on other aspects such as heat dissipation and sensorial comfort. The inter-relationship between a garment (PPE), an individuals body size and shape and other clothing items worn determines the fit (Ashdown and DeLong, 1995), which has been identified as essential to the user's satisfaction. A poor fitting garment will be uncomfortable and movement could be hindered (Watkins, 1995). Also, poorly fitting garments can have several other detrimental effects, such as restricting cardio-vascular flow, causing skin abrasions, inducing skin irritations and reducing heat dissipation (Milenkovic *et al.,* 1999), which will have a negative affect on perceived comfort

4.2.1 Range of motion

Various items of PPE, including gloves and knee protectors, have been found to have detrimental affects on the range of motion of the wearer, causing a loss of dexterity and mobility, thus affecting the ability to perform desired movements and tasks, such as gripping tools and equipment (Bellingar and Slocum, 1993; Parssons and Egerton, 1985; Saul and Jaffe, 1955; Sheridan, 1954; Tremblay, 1989). Typically the influence of PPE on performance is measured through a user's ability to conduct routine movements and their range of motion (ROM) or reach capacity is then compared between garments or to the unrestricted motion of the naked body (Huck, 1991). Range of motion can be measured using different methods including exercise protocols (Ruckman *et al,* 1999), studying wearers' movements on film (Lawson and Lorentzen 1990) and observing garment strain in photographs (Ashdown and DeLong 1995). More commonly, however, joint angles are studied; these have been measured using goniometers, Leighton flexometers, electrogoniometers, or through more complex photographic and 3D motion analysis techniques (Gehlsen and Albolm, 1980; Watkins 1984).

Research within the area of PPE has identified the need for analysis of the effects of fit on users' abilities to perform required movements (Adams and Keyserling, 1996) to enable the development of comfortable, well fitted PPE, without sacrificing protection or performance (Bellingar and Slocum, 1993; Huck *et al*, 1997). The fit of protective garments can have several detrimental affects on protective aspects, as well as comfort and functionality (Keeble *et al* 1992). For example, if the PPE is loose fitting within cricket, it could allow a ball to strike the batsman's leg through gaps between pad and shin, reducing protection due to poor fit. Also, to encourage use of PPE, comfort and function must be optimised otherwise end-users will be less likely to use the product, increasing the risk of injury (Bellingar and Slocum, 1993).

Inadequacies of functional clothing have been identified in a range of activities from grass fire fighting (Huck *et al,* 1997) to ice hockey (Watkins, 1977) and golf (Wheat and Dickson, 1999). These inadequacies can be due to a number of reasons from fit (Wheat and Dickson, 1999) to inappropriate design (Huck *et* al, 1997). Wheat and Dickson (1999) found that end-user satisfaction strongly correlated with good fit and aesthetically pleasing uniforms. Restricted movement was also reported to be a cause of dissatisfaction for cyclists (Casselman-Dickson and Damhorst, 1993) suggesting that fit and the garment's influence on range of motion could be of key importance to the comfort of the performer.

Huck *et al* (1997) found that altering a garment's fit in one area can increase movement in one dimension, but, restrict it in another. They demonstrated that adding an elasticated waist at the back of protective overalls increased trunk flexion but the consequence was decreased knee and shoulder flexion. These results demonstrate the need for an understanding of the nature of the movements performed whilst wearing the protective equipment, allowing maximisation of mobility, without sacrificing movements in other areas of importance for optimum performance.

Research within PPE has identified that reduced mobility is linked to material thickness, weight, protection level and design (Bellingar and Slocum, 1993; Huck and Kim, 1997; Watkins, 1995). The effect of design was demonstrated by Huck and Kim (1997) who maximised the flexibility of a garment through elasticated panels and ensured good fit through correct torso length, which increased the range of motion for a specific movement (for example trunk flexion) by up to 28.7%.

There has been a substantial amount of research regarding the fit of a garment and its influence on performance. This research, however, has historically based its findings on simplified movements and maximal flexion/extension tests, rather than realistic actual movements (Hu *et* al 2007; Huck and Kim, 1997; Li *et* al 2005). The use of these generic tests for specific items of sports PPE is questionable because they do not necessarily represent the movements made within the sporting environment. The development of a specific test protocol enabling the testing of sports equipment in a more representative manner is, therefore, required.

It can be seen from the current literature that, before improvements to the design of the PPE can be made, a greater understanding is required of the effect of PPE on movement and performance. To do this effectively, a suitable method needed to be developed to ascertain the degree to which movement is restricted, and the manner in which the performer's motion is inhibited, whilst performing realistic movements. The aim of this section is to develop a suitable methodology for assessing the effects of PPE on range of motion, perceived restriction and player performance.

4.3 Quasi-static vs. dynamic methods

There are several techniques which have been used to measure range of motion within the literature, including both quasi-static and dynamic methods. Each measurement technique has inherent strengths and weaknesses which make them suitable for specific types of measurement. Therefore, prior to determining which data collection technique was most suited to this study, the advantages and disadvantages of several different methods were evaluated.

4.3.1 Exoskeletal measurement devices

Two common measurement tools used when analysing joint angles are inclinometers and goniometers. Inclinometers work by measuring angles of joints with respect to gravity, by generating an artificial horizon, then measuring angular tilt with respect to that line. Digital and ferrofluidic inclinometers are now available which utilise 'cantilever force sensors' and 'magnetic force' to measure angles respectively (Ando *et al.*, 2007). Goniometers, in comparison, measure the angle between two joint axes. As with inclinometers, digital goniometers are available which utilise an electrical potentiometer to allow continuous data logging during a motion. Although inclinometers are inexpensive, and have a high resolution of ±0.1° (Hua-Wei *et al.*, 2005), their suitability for measuring joint angles is debatable as alignment errors can occur and they are more suitable for measuring the 'tilt' or angle of one plane relative to a horizontal plane, rather than about a joint. Even using clinicians to align the inclinometers can give unreliable results (Rondinelli, 1992). Goniometers are designed to measure joint angles but are exoskeletal devices that cross the joint, potentially interfering with movement. Furthermore any shift from their original orientation leads to errors in angle estimation (Veltlink *et al,* 1996).

4.3.2 Video analysis

Another popular method for measuring and analysing human movement is digital videography, where motions are captured using one or multiple cameras, depending on whether a 2D or 3D analysis is needed. Once the movement has been captured, software packages such as Quintic and Silicon coach can be used to digitise and analyse the motion. The use of digital videography is relatively inexpensive compared to dedicated 3D motion analysis systems and has the added benefits of being suitable for use both in a laboratory environment as well as in a game situation. A limitation of this method is the slow sampling rate associated with standard video cameras (typically 25Hz), which can result in large gaps in movement data and the possibility of key events being missed. Video analysis is also susceptible to errors within the digitisation phase, as blurring of fast moving objects can occur as a result of low shutter speeds, which can be required when collecting data in the field, due to insufficient lighting. Also the process of co-ordinate digitisation requires a great deal of post processing (Bartlett, 2007). To overcome some of these limitations, high speed video can be used, reducing gaps within the data, through increased frame rates >200 Hz. However, the use of high speed video increases the cost substantially and as with all imaging incurs focal issues when the movement is not parallel to the focal plane of the camera (Holmes, 2008).

4.3.3 3D Motion analysis package

3D motion analysis packages have been used for a wide range of measurements within engineering, animation and human sciences (Ohta *et al,* 2007; Riley *et al,* 2007). There are two main classifications of 3D motion analysis systems - active and passive systems. Passive marker systems include Vicon, and Pro Reflex, which utilise multiple cameras to track retro-reflective markers placed on the object of interest. The advantages of these systems is a combination of high sampling rates, accuracy and resolution, allowing 3D movements to be captured and measured in terms of 3D joint positions and velocities. The disadvantage with these passive systems is the need for multiple cameras, resulting in substantial cost, to maintain line of sight between markers and camera. If marker occlusion occurs, data becomes intermittent and algorithms have to be used to predict marker trajectories which do not always produce accurate results. In addition, markers do not have specific identities, resulting in each marker having to be labelled individually by the investigator, increasing risk of error when trajectories of markers cross.

Active systems such as CODA (Cartesian optoelectronic dynamic anthropometer) utilise LED's for markers, which flash in sequence and, therefore, the identity of the marker is known, whereas passive systems infer marker identity from continuous observation. The advantages of these systems is that they can operate with only one head unit and, due to a wide viewing angle of approximately 80 degrees, a large capture volume can be measured. The problem with active systems is that each marker needs a drive box for power and communication purposes, potentially making them harder to attach without impeding movement or affecting results, and adding weight to the object being analysed. As with Vicon, data can be intermittent if markers are occluded from the camera, resulting in inaccuracies.

4.3.4 Determination of measurement system

The different measurement systems were analysed in terms of appropriateness and availability. After considering exoskeletal devices, video analysis and 3D motion analysis, it was determined that 3D motion analysis was the most suitable method for this study, due to its high sampling rate, accuracy, and resolution. Also the markers utilised within these methods impose minimal restriction on movement, allowing participants to move freely and as naturally as possible.

For this study, two 3D motion analysis packages were available, one active system, CODA, and one passive system, Vicon. A pilot test was conducted using both systems to evaluate their appropriateness for this analysis. From the pilot study, Vicon was deemed a more suitable system due to the greater number of head units reducing marker occlusion throughout the motion. Also the powerful Bodybuilder software which accompanies the Vicon system enables fast and automated data analysis, as well as allowing representative markers to be used when typical anatomical landmarks are not accessible or useable.

4.4 Development of Measurement technique

4.4.1 Shot selection

The first step in developing a suitable method for assessing the effect of different cricket leg guards on shot kinematics and performance was to determine which movements are perceived to be most restricted whilst wearing cricket pads. There are twelve different cricket strokes typically played, which can be classified into two sub-groups of front or back foot strokes. Front foot strokes are traditionally aimed at fuller length deliveries, whereas back foot shots are normally used when playing at shorter deliveries (Morrison, 1998). Observations of the movements about the knee and ankle joints for the different strokes played within a match indicated a difference in the movement requirements between the sub-groups, with back foot shots requiring finer rotational movements such as inversion and eversion at the ankle, with a greater emphasis on speed of motion rather than ROM, compared to front foot shots. Although there are obvious differences in movement patterns between shots, it is difficult to determine which are restricted more by leg guards, therefore a questionnaire was utilised to determine cricketers' opinions and identify shots of interest for further investigation.

Thirty eight UCCE (University Centre of Cricket Excellence) students completed the questionnaire in Appendix 3. They were asked to rank which of the following shots cricket leg guards restricted the most - full toss, hook, backward defensive, pull, backward attack, forward defensive, drive and sweep shots, with 1 representing most restricted and 8 the least restricted. The results were then analysed using Friedman's test, as described in Section 3.2.3, to determine whether there were any significant differences in perceived restriction of different shots. The Friedman test statistic, T=113.9 was greater than the Chi-square value of 18.5 for k=8 (significance level of 0.01), indicating significant differences in perceived restriction between shots. Fisher's LSD_{rank} (least significant difference) was then used, to identify which of the shots differed significantly. The perceived restriction of a shot was considered to be significantly different to another, if the rank sums for the two shots differed by more than one LSD_{rank} (41.9). The rank sum for each shot is shown in Figure 4.1 with a bar equal to the value of Fishers LSD_{rank} evenly distributed about the rank sum. If the bars do not overlap then the rank sums must differ by more than the value of LSD_{rank} and, therefore a significant difference was perceived between shots. It can be concluded that leg guards are perceived to cause more restriction when playing a sweep shot compared to a drive and cause significantly less restriction for all the other shots. There were no significant differences between the rest of the shots except the full toss which was perceived to be the least restricted by a significant amount. Therefore, the three shots that were selected for further analysis within this study were the sweep and drive shots and also the pull shot as it was the most restricted back foot shot.

4.4.2 Subjects

Nine UCCE first and second team top order batsmen participated in the range of motion testing; the cricketers had a mean age of 19.6 years (±0.8 years). These players were deemed to have good technical ability and be familiar with wearing protective equipment whilst playing cricket.

4.4.3 Test protocol

Each of the nine participants performed five repetitions of each shot striking a suspended ball, which had been set at an appropriate height and position for each shot, such that the individual would be at maximal reach (Figure 4.2). A suspended ball was used to ensure any differences in movement were caused by the leg guard and not by variations in delivery and to prevent any equipment from being struck. Five different conditions were evaluated:

1. No pads worn (NP)
2. Puma, Ballistic pads (P1) (Figure 2.2)
3. Aero pads (P2) (Figure 2.2)
4. Woodworm premier pads (P3) (Figure 2.2)
5. 0. 9 kg ankle weights representative of the heaviest pad (weighted comparison).

A weighted comparison (WC) was included to determine if any changes in movement were due to additional weight or restricted joint motion. Each shot was captured using a Vicon system, the setup is described further in section 4.5. To synchronize all trials, the suspended ball was marked with a piece of retro-reflective tape, so that time of impact could be identified.

4.4.4 Measurement of performance

To accompany the kinematic results from Vicon, impact location data was also gathered to identify any detrimental affects on shot performance caused by movement constraints. Players were asked to set up for each shot at maximum reach without any pads on, ensuring they could still impact the ball on the estimated sweet spot of the bat provided, which was identified in accordance with Brooks *et al* (2006) work on sweet spot location in cricket bats. Once the player had found the appropriate starting position for each of the shots, their foot positions were marked to ensure a consistent start position. An impact label for the bat was constructed using a piece of plain paper attached to the face of the bat with a sheet of carbon paper placed over the top. The impact locations of each shot for all five conditions were recorded to allow comparisons between conditions in terms of accuracy and consistency of strike.

4.4.5 Perceived Restriction

A post use questionnaire was completed by the participants to evaluate the perceived restriction of each of the pads (P1, P2 and P3) (Appendix 4). Within this questionnaire rankings regarding perceived restriction and comfort were gathered through the use of line scales, which allowed the subjects to place a mark at a point that represented how restrictive and uncomfortable each pad felt compared to batting without pads. Participants were also asked to identify any sources of perceived restriction on a schematic diagram of the legs. This data was collected to enable comparisons to be made between perceived and actual movement restrictions.

4.5 Vicon data collection

4.5.1 Calibration

An eight camera Vicon system was set up to capture the 3D motion data as depicted in Figure 4.3. Each camera unit consists of a video camera, strobe head assembly, lens and an optical filter, as shown in Figure 4.4. The infrared light produced by a ring of light emitting diodes (LEDs), is reflected off retro-reflective markers placed on the subjects' body and captured by the video camera, producing a high contrast image.

Prior to data collection, a two phase calibration was completed in accordance with the Vicon user manual, consisting of a static and dynamic calibration, using the Ergocal calibration frame and wand (Figure 4.5). Once both phases had been performed, the system calculated the error within each camera; if this value was too high the calibration was deemed unacceptable, resulting in the cameras being adjusted, prior to recalibration. After calibration, the system calculated a mean residual value of 0.613mm (±0.07mm) and was deemed acceptable in accordance with previous studies (Roosen, 2007). The residual value is the root mean square of the distance between a ray projected from the centre of the strobe ring to the centroid of a retro-reflective marker and the location on the lens where the reflected ray from the marker hits (Roosen, 2007).

4.5.2 Marker set up

A standard marker set up was not appropriate for this study, as markers placed on the standard anatomical land marks at the knee and ankle would not be visible due to being covered by the protective equipment. Therefore, the CAST technique was used (Cappozzo *et al*, 1997; Hobbs *et al*, 2006; Lloyd *et al*, 2000). This method required three or more markers to be placed on the relative body segment which enabled a new local coordinate system to be created from the marker positions that was then related to the global coordinate system. Once this local coordinate system had been created, the position of the joint centre was calculated relative to the marker cluster, through a static trial where markers were present on the anatomical landmarks. For the static trial, the participant was captured standing in the centre of the capture volume in the anatomical position (feet

Marker	Definition	Position
LASI	Left anterior super iliac	Bony protrusion of the anterior superior iliac.
RASI	Right anterior super iliac	
LPSI	Left posterior super iliac	Dimples created by the posterior super iliac.
RPSI	Right posterior super iliac	
LTHIS	Left thigh superior	Placed on the left and right thigh
RTHIS	Right thigh superior	
LTHII	Left thigh inferior	Placed on the thigh approximately 2 inches
RTHII	Right thigh inferior	below the LTHIS or RTHIS.
LTHIA	Left thigh anterior	Placed on the thigh, 1 inch below the L/ RTHIS
RTHIA	Right thigh anterior	and 2 inches forward of the line between L/
		RTHIS and L/ RTHII.
LKNEL	Left knee Lateral	Along the flexion/ extension axis of rotation at
RKNEL	Right knee lateral	the lateral femoral condyle.
LKNEM	Left knee medial	Along the flexion/ extension axis of rotation at
RKNEM	Right knee medial	the medial femoral condyle.
LANKL	Left ankle lateral	Along the flexion/ extension axis of rotation at
RANKL	Right ankle lateral	the lateral malleolus.
LANKM	Left ankle medial	Along the flexion/ extension axis of rotation at
RANKM	Right ankle medial	the medial malleolus.
LMTPL	Left metatarsal lateral	Dorsal aspect of the fifth metatarsal head.
RMTPL	Right metatarsal lateral	
LMTPM	Left metatarsal medial	Dorsal aspect of the first metatarsal head.
RMTPM	Right metatarsal medial	
LHL	Left heel	Placed on the back of the foot.

Table 4. 1: Marker set and anatomical position, with redundant markers for static capture only in bold

apart, arms away from the body with palms facing forward ensuring no markers were occluded) for 10 seconds; a redundant marker set of 24 retro-reflective passive markers of 14mm diameter were attached, as illustrated in Figure 4.6 (Table 4.1). For the NP trials, the full marker set up was also used to assess the accuracy of the cluster markers when compared to markers placed on anatomical land marks. Once the static and NP trials were complete, superfluous markers were removed; these included the medial and lateral knee and ankle markers for both legs (Table 4.1).

4.5.3 Movement data collection

Once a static trial had been captured the participant was asked to perform each of the three shots (pull, drive, and sweep) five times for each of the four conditions; for each participant the order was randomised to prevent order effects.

4.6 Data processing

4.6.1 Reconstruction of movement

The 3D positions of each marker were calculated within the Vicon software, through the combination of the 2D information from each camera and calibration data; this process was conducted in software packages Workstation and Bodybuilder. To optimise the reconstruction process, camera settings were manually adjusted to reduce flickering and jumping of markers through a trial and error process.

4.6.2 Labelling

Once the 3D motion data had been successfully reconstructed, all the markers needed to be identified and labelled. A frame was chosen where all markers were in view, with each marker being labelled from top to bottom, left to right. This systematic approach was used for all trials to minimise risk of error within the labelling process. The entire motion file was then checked to ensure occluded markers were relabelled after disappearing from view. Generally gaps within marker trajectories due to occlusions can be filled through one of two methods, a spline-fill or by copying the trajectory of another marker. Both methods have their limitations, for example, a spline-fill can create inaccurate data where there are sudden changes in motion pattern and therefore should only be used to fill small gaps within the data. To prevent inaccurate data being collected, a maximum fill size was set at 10 frames; for any gaps in the data greater than this, markers from the same segment were tracked, as this method identifies changes within the trajectory with a greater degree of accuracy.

4.6.3 *Modelling and exporting data*

The data could now be processed using the software package Bodybuilder which transforms marker positions into kinematic and kinetic data. For this study, a specific lower-body model was written defining each segment (Appendix 5). Through this code, the joint centre location could be calculated from the cluster markers allowing Euler angles (rotation sequence zyx) between segments to be calculated. Once the model had been executed on the motion data files, all trials were synchronised by cropping each time series to include 1 second before and after impact, which was deemed suitable as it enabled the whole action to be analysed for all trials. From the data, the left knee angle (LKA), right knee angle (RKA), left ankle angle (LAA) and right ankle angle (RAA) were calculated. Flexion/extension angles were analysed throughout the entire movement as well as at specific points within the batting motion (0.5 s before impact, impact and 0.5 s after impact). A Shapiro-Wilk test was used to establish the normality of data sets. Providing the data was normally distributed ($p>0.05$) a one-way repeated measures ANOVA was used to determine if there was a main effect between conditions, secondly a Tukey-Kramer post-hoc test was completed to determine which results were significantly different ($p \leq 0.05$).

4.7 Results

4.7.1 *Joint angles*

The initial analysis focused on the accuracy and suitability of the marker clusters. To determine the accuracy of the 3D model, joint centre positions and joint angle (flexion/extension) at the knee and ankle when calculated using the clusters were compared to those obtained using the markers on the knee and ankle. Table 4.2 outlines difference in joint centre location for all nine subjects, with a mean root mean square (RMS) of 1.11 mm and 1.29 mm for the knee joint centre (KJC) and ankle joint centre (AJC) respectively. The difference between joint angles at the knee and ankle when calculated using the clusters were compared to the angles obtained from the markers on the knee and ankle for the NP trials. Figure 4.7 illustrates the difference in measurement between cluster and landmark measurements obtained from an individual NP trial for all three shots of Subject 5, which was a good representation of all trials. The results illustrate a maximum error within ±4° for all three shots. This magnitude of error was deemed suitable as previous studies have identified that errors of 4.7° can be caused by skin artefact (Reinschmidt *et al*, 1997).

Subject	KJC error RMS (mm)	AJC error RMS (mm)
1	0.78	1.23
2	1.70	1.32
3	0.71	1.26
4	1.23	1.36
5	1.55	0.82
6	0.49	1.67
7	0.76	1.13
8	1.65	1.42
9	1.15	1.47

Table 4. 2: Root mean square (RMS) difference in joint centre position at the knee joint centre (KJC) and ankle joint centre (AJC) when calculated using the knee and ankle landmarks and the cluster markers for all 9 subjects

Further analysis of the data was conducted using the following procedure. Initially, a qualitative analysis was performed to observe any differences in movement patterns between participants as well as between conditions. All nine subjects were then analysed individually by assessing differences between conditions across the whole time series, and at three intervals 0.5 seconds before impact, impact and 0.5 seconds after impact. Differences in joint angle between conditions for each subject and for the entire group were statistically analysed. Finally, the approximate entropy for all conditions was calculated for all nine subjects to compare the regularity of the movement throughout the entire time series (Pincus, 1991).

The analysis procedure resulted in a large amount of data; therefore, the following section presents the results for the left knee, as this is subject to the largest ROM throughout all three shots. Figure 4.8 illustrates the mean movement pattern of the LKA for the three different shots for each of the nine participants in the NP condition. The angle measured is the flexion/ extension of the knee, where an angle of 180° represents a straight leg and 0° a fully flexed leg. Although, the movement time series for all subjects follows a similar sequence, for the drive and sweep, differences in the magnitude and timing of flexion and extension from person to person can be seen, highlighted by the maximal standard deviations between subjects of 15.53°, 19.08°, 23.5° at any one point for the drive, sweep and pull, respectively. It can be seen that the pull shot is more dependent on individual technique as there is not a consistent movement pattern exhibited by all players, whereas the drive and sweep follow a more consistent pattern. For both the drive and sweep shots the movement pattern consists of a slight flexing of the knees as the players prepare to play the shot (-1 to -0.8 seconds), the straightening of the leg as they take one stride forward to set the front foot in the correct position (-0.8 to -0.4 seconds) and finally flexing the knee to get into the correct position as they play the shot (-0.4 to 0 seconds).

Figures 4.9 to 4.11 illustrate the results for three of the subjects (3, 5, and 9) for the sweep; these subjects were chosen as the combination of their results was deemed to be representative of all the data. The greatest amount of flexion and extension occurs at the left knee whilst performing the sweep, and so, this angle was used to illustrate the findings. Parts a) to d) of Figures 4.9 to 4.11 compare each subject's mean motion without pads to the other four conditions, whilst all five motions are overlaid in part e). Part f) illustrates the consistency of the motion regardless of condition. The results demonstrate that the pads do affect individual subjects, but in different ways and to different degrees. In particular, Subject 3 had less flexion of the knee post-impact ($t>0$) when wearing P2 and P3 compared to the NP, P1 and the WC (Figure 4.9). The padded and WC conditions appeared to increase extension of the leg as the player steps forward to get into position ($t=-0.5$ to -0.2) for Subject 5 in comparison to batting bare-legged (Figure 4.10), whereas, Subject 9 demonstrated less flexion of the knee post impact in all padded and WC conditions when compared to NP (Figure 4.11).

The time series were investigated in more detail at -0.5, 0 and +0.5 seconds to determine if there were any significant differences within the movement patterns between conditions. Figures 4.12 to 4.14 illustrate the mean left knee angle during the sweep at each time interval for all nine participants. A Shapiro-Wilk test for establishing the normality of data sets was performed, identifying the data for all three time intervals was normally distributed ($p>0.05$). Therefore, to test for significance, a one-way ANOVA was utilised; no significant differences were found between any of the five conditions at any of the three time intervals ($F=<3.72$, $p>0.241$), which could be expected due to the majority of differences being within the bounds of the standard deviations. Analysing the results on an individual basis rather than as a group did reveal individual cases where movement appeared to be significantly restricted due to different pads but the findings were specific to each individual and no clear trend could be found for all of the subjects.

Finally, an approximate entropy analysis was performed on all trials to assess the regularity of each movement and determine if leg guards altered the way in which the leg moved. The approximate entropy (ApEn) was calculated through the use of the MATLAB code created by Challis (2001) which represents the method developed by Pincus (1991). ApEn takes a value of 0 upwards with 0 representing a completely regular signal and the greater the ApEn value the more irregular. In this study, a run length of 2 and filter length of 0.5 were used. Table 4.3 shows the range and average ApEn; to determine if there were any significant differences in ApEn between conditions an independent samples t-test was performed. No significant differences between conditions ($p>0.174$) were found.

Although, the LKA results have been focused on within this section, the LAA, RKA and RAA were all analysed using the same process. As with the LKA, there were no significant differences ($p>0.263$) found between the five conditions at any of the time intervals (-0.5 s, 0 s, or +0.5 s), or in the regularity of movement ($p>0.341$).

	N/P	P1	P2	P3	Weight
Range	0.08-0.33	0.13-0.33	0.15-0.3	0.15-0.37	0.13-0.30
Mean	0.22	0.22	0.23	0.24	0.23
Stdev	0.10	0.07	0.06	0.10	0.07

Table 4. 3: ApEn values for all 5 conditions

4.7.2 Impact location

During the testing, the impact location on the bat was recorded to determine if wearing cricket leg guards restricted movements and affected shot performance. Figure 4.15 illustrates an impact label for Subject 5 performing a pull shot whilst wearing no pads; the impact data was analysed by measuring the distance between the approximate sweet spot of the bat and the centre of the recorded impact. From this, it was possible to determine if cricket pads have a negative affect on shot performance in terms of accuracy (how close the impacts are to the datum) and consistency (how well clustered the impacts are). Figures 4.16 to 4.18 illustrate the location of all participants' impacts for each condition for the three shot types. Each ball impact was measured as an x and y distance from the sweet spot datum, with positive directions indicated in Figure 4.15. The results for the nine different players were compiled and Figures 4.19 to 4.21 show the mean impact location for each condition with an ellipse used to illustrate the standard deviation in the x and y axes. From the impact data, maximum mean differences between any 2 conditions of 8.9mm, 12.13mm, and 7.4mm in the x direction and 10.9mm, 13.95 and 8.56mm in the y direction were found for the drive, pull and sweep respectively. In relative terms, this is a difference of less than one fifth of the diameter of a cricket ball (78mm), this small difference was reflected within the ANOVA results, which indicated that there were no significant differences between any conditions across all three shots (F=0.637, p=0.619).

As a measure of consistency, all shots were analysed through the use of ellipses (Figure 4.19 to 4.21) depicting the variation in both the x and y direction about the mean for each of the five conditions. Differences in ellipse size, shape and position are observable, however, Bartlett's test for homogeneity of variances revealed no significant differences, due to the homogeneity of variance equalling 3.42, 4.39, 1.98 for the drive pull and sweep respectively, which are all lower than the Chi-squared value of 9.49 (for k=5 at a significance level of 0.05).

4.7.3 Perceived restriction

To determine if there is a relationship between perceived and actual restriction, players perceptions were collected after all shots had been played using each of the pads. All three pads were compared on one scale allowing a rank order to be produced, with the pad deemed the most restrictive given a rank of 1 through to a rank of 3 for the least restrictive pad. The ranks for all nine participants were then summated for each pad to give a rank sum to be determined and Fisher's LSD_{rank}, was then used to determine significant differences in perceived restriction between pads. The results suggest that the participant's perceived P3 to be significantly more restrictive than P1 and P2 (Table 4.4), due to the difference in rank sums being greater than the value of LSD_{rank} (8.32). No significant difference between P1 and P2 ($p<0.05$) was found.

	Restriction		
Subject	P1	P2	P3
1	2	3	1
2	3	2	1
3	2	3	1
4	3	1	2
5	1	3	2
6	2	3	1
7	3	2	1
8	2	3	1
9	2	3	1
Rank sum	20	23	11
LSD_{rank}	8.3	.05sig	

Table 4. 4: Rankings of perceived restriction for P1, P2 and P3

The participants were also required to record on an illustration of their legs the regions of discomfort. The results from all subjects were compiled and depicted on a schematic diagram of both legs from an anterior and posterior perspective. Figure 4.22 illustrates the results through the use of a colour scale representing the frequency of identification of a specific location as a source of discomfort, ranging from light yellow representing 1 to dark red representing 6+. From the results it can be seen that P3 caused a greater number of sources of discomfort, with 10 locations being highlighted compared to seven for P2 and six for P1. A higher response frequency was also found for P3, with all 9 participants identifying the back of the knee on both legs as being a major source of discomfort, whereas on the other two pads, no area was identified more than 5 times.

4.8 Discussion

The influence of different leg guards on batting kinematics and shot performance in cricket were analysed within this study by comparing actual and perceived restriction. A technique involving the use of cluster markers was developed to assess leg kinematics whilst wearing leg guards due to appropriate anatomical land markers being covered by the protective equipment in question. With the use of cluster markers on the foot and thigh, errors were present in joint angle calculations when compared to those measured from the appropriate anatomical landmarks, however, these errors were <4° for all shots and can be attributed to skin artefact, which has been found to produce errors of up to 4.7° when measuring flexion/extension of the knee (Reinschmidt *et al,* 1997). The results demonstrated that leg guards can influence ROM for some players, but the effect is individual to the specific player and no consistent trends could be found for all players. The impact location data also supported these findings, as leg guards were not found to affect shot accuracy or performance. However, seven out of the ten participants perceived P3 to be more restrictive than P1 and P2, whereas only three participants were found to be restricted by P3, of which only 2 ranked it as the most restrictive. To gain a greater understanding of why players perceived some pads to be more comfortable than others, they were asked to identify sources of discomfort. P3 was identified as having more areas that cause discomfort, which were identified with greater frequency than for the other pads. One area identified by all 9 participants was the strap located behind the knee of P3 and appeared to be the largest difference between the three padded conditions.

The results within this chapter suggest that cricket leg guards do not significantly affect shot kinematics or performance; however, different pads do elicit varying degrees of perceived restriction. These findings warrant further analysis of the interaction between the player and the leg guard, investigating the relationship between strap design and perceived restriction, as well as further analysis determining the effect of leg guards on running performance.

Chapter 5

The effect of cricket leg guards on running performance

The studies presented so far in this thesis have highlighted that sports PPE is often perceived to have a negative affect on performance. During interviews with cricketers, they revealed that leg guards can inhibit running performance and that the degree of this restriction varies between pads. Therefore, the aim of this chapter was to determine if running performance was negatively affected as a result of wearing cricket leg guards and, if there was a negative affect on performance determine which part of the run was most affected (running or turning) and the cause.

The initial part of this chapter describes the method used to measure the effect of leg guards on running performance when compared to running without pads. The second part details the development of a dynamic test method for assessing running kinematics and ground reaction forces (GRF) to determine possible causes of decreases in performance, as well as to measure pad movement about the leg.

The majority of literature regarding the affect of PPE on range of motion has focused on industries such as the armed forces, services (police etc) and chemical hazard protection, as discussed in Section 4.2. Over the past decade, advances in research regarding sports PPE have started to be made with Green *et al.* (2000) identifying the need to develop a suitable measurement technique to assess the influence of different protective knee braces have on American football manoeuvres. Using dynamic test methods in realistic environments, Green *et al.* demonstrated that the detrimental affects of different knee braces could be assessed and compared to one another to allow end-users to choose a product that will help them to maximise performance. The most relevant study of this type was conducted by Loock *et al.* (2006), where the effect of cricket leg guards on running performance was measured. Three leg guards were tested weighing 1.85 kg, 1.70 kg and 1.30 kg per pair but were not found to significantly affect the overall time taken to complete three runs or the time taken to turn between each run when compared to one another. Although this testing suggests wearing different leg guards does not affect performance, since this testing was completed new lightweight pads have been introduced to the market and required testing. To build on the testing completed by Loock *et al.* (2006), a comparison between running with and without pads was required to determine the true effect of cricket leg guards on running speed, rather than solely comparing different brands of pad. To achieve this, a two-stage methodology was adopted. The first stage focused on further developing previous work by Loock *et al.* (2006) assessing the effect of cricket leg guards on running performance when compared to running without leg guards. The second stage aimed to further explain the results found within the first stage of testing, through the use of different biomechanical techniques which looked at possible causes of reduced running speed. All methods used within both stages of testing were approved by the Loughborough University ethics committee prior to subject recruitment.

5.1 Stage 1: Running time analysis

5.1.1 Method

Ten male cricketers with a mean age of 19 years old (±0.8 years), all playing at county first or second team level, participated in a running time study. Each participant ran three consecutive runs whilst carrying a bat, this was repeated four times with 1 minutes rest between each three, starting with their lead foot on the crease each time. This sequence of four sets of three runs was repeated for five different conditions (No pads, Pad 1, Pad 2, Pad 3 and a weighted comparison). Running performance was evaluated using four smart speed light gates (Fusion Sport) (Figure 5.1) positioned at each crease and 5 meters from each crease, as shown in Figure 5.2, each light gate was set at shoulder height to minimise the chance of the bat or hand breaking the beam, maximising consistency. The two light gates positioned on each crease were used to measure "total-time" taken to complete 3 runs and the two gates positioned 5 meters before each crease were used to measure "turn-time", which was represented by the time taken to run from 5 meters before the crease to 5 meters after. Each player was given 15 minutes rest between conditions to minimise any effects of fatigue, and condition order was randomised to prevent order effects. A no pad (NP) condition was included to determine an unrestricted benchmark against which the different pads could be compared. The three pads tested within this study were chosen as a suitable representation of the current market, with Pad 2 (P2) representing the more modern design of pads, constructed of a single piece of moulded closed cell polyethylene foam. Pad 3 (P3) represented the more traditional pad construction, comprising of multiple foams and pieces of cane for added support. Pad 1 (P1) was included as a compromise between the two extremes, and again had a multiple foam construction (Figure 2.2). As well as varying in construction the pads also varied in mass, with P1, P2 and P3 having an individual pad mass of 0.85 kg, 0.5 kg and 0.9 kg per pad respectively. In order to determine if any impedance in running performance was solely attributable to additional mass, a "weighted comparison" (WC) was conducted. A 0.9 kg mass was positioned on the shin of each leg in order to be comparable to the heaviest pad used (P3), but imposed minimal restriction around the knee and ankle, and had much less bulk (Figure 5.3).

5.1.2 Statistical analysis

The Shapiro-Wilk test was used to establish the normality of data sets. Providing the data was normally distributed ($p>0.05$), a one-way repeated measures ANOVA was used to determine if there was a main effect between conditions, secondly a Tukey-Kramer post-hoc test was completed to determine which results were significantly different ($p \leq 0.05$). A Gabriel comparison interval was used to illustrate where significant differences were identified between conditions (Gabriel, 1978). The Gabriel comparison was calculated by taking the standard error of the mean for a group and multiplying it by the studentized maximum modulus, this was then multiplied by the square root of one-half. The Gabriel comparison is then used to illustrate the upper and lower limits for $p=0.05$, with no overlap between the groups indicating a significant difference.

5.1.3 Results

The mean "total-time" for three runs was calculated individually for every participant for each condition, a consistent trend was found across all participants, as illustrated in

Figure 5.4. It can be seen that all the cricketers produced their fastest times when not wearing pads or an additional mass. The one-way ANOVA results identified that there was a significant difference between conditions (F=10.34, p=0.000) in terms of "total-time". The post-hoc results revealed that the "total-time" for all three padded conditions and the WC were significantly slower than the NP condition (p<0.02) (Figure 5.5a). "Total-time" increased by up to 0.5 seconds when comparing P3 with the NP condition (p=0.000), which equates to approximately 3 meters when at a speed of 6m/s. Differences between padded conditions were also identified with P3 resulting in significantly slower times in comparison to P1 (p=0.011), P2 (p=0.001) and the WC (p=0.019). P3 was the heaviest of the three pads, however, the players were able to run significantly faster when wearing the same mass as P3 strapped to their shins (i.e. the WC). In fact, no significant differences were found between pads P1, P2 or the WC (p>0.821), despite considerable differences in mass, suggesting that the increase in "total-time" is not solely attributable to additional mass.

As well as "total-time", "turn-time" was measured, the data presented is the mean time taken to turn, with the data for turn one and two being combined, as there was no significant difference found between turns within a trial (p=0.931). The same statistical tests were performed on this data as described for the "total-time" analysis, with no significant differences between conditions emerging (p>0.864) (Figure 5.5b), suggesting that differences in time were due to the negative effects of pads on straight line running, rather than on time taken to change direction.

These results suggest that running performance is inhibited by cricket pads, due to a negative effect on straight line running speed. The resultant increase in "total-time" is not solely attributable to pad mass, as there were no significant differences between P1, P2 or the WC, despite a difference of up to 0.4 kg in mass. Also P3 was found to inhibit performance to a greater degree than the WC despite being of equal mass. These results suggest there are further causes of this decrease in performance, including possible effects on running kinematics, and so this was studied further in the follow-up test described in the next section.

5.2 Stage 2: Running Biomechanical Analysis

The initial testing identified the need for further analysis of how cricket leg guards affect the end-user in terms of running kinematics, in order for the design of cricket leg guards to enable maximal performance. There has been a substantial amount of previous research into the biomechanics of running (Cavanagh and Lafortune, 1980; Gottschall and Kram, 2005; Novacheck, 1998), through which two major factors have consistently been related to sprinting velocity, these are ground reaction force (GRF) and joint angular motion (Hunter *et al*, 2005). GRF has been defined as a force equal in magnitude and opposite in direction to that applied to the ground by the foot during the stance phase. For the purpose of analysing running kinematics, the GRF can be decomposed into three orthogonal components, the anteroposterior component, the vertical component and the mediolateral component. Cavanagh and LaFortune (1980) categorised runners into three distinct classifications based on the location of their centre of pressure (COP) at the time of initial contact. The three classifications have been identified as forefoot, midfoot and rearfoot strikers. Forefoot strikers are runners whose COP is over the front third of the foot at initial contact, whereas a runner is classified as a midfoot or rearfoot striker when the COP is over the middle third or most posterior third of the foot at initial contact respectively. The shape and magnitude of each GRF component has been found to be dependent on classification of runner.

The anteroposterior forces generated during running are directly associated with the horizontal acceleration of the body during the support phase and have been characterised as being biphasic. The initial phase is termed the braking force, typically occurring at the beginning of the stance phase and acts in a posterior direction, therefore, opposing forward motion, resulting in a period of deceleration. The second phase is termed the propulsive force, which occurs after the braking force in an anterior direction (in the direction of locomotion) (Hunter *et al.* 2005, Munroe *et al.*, 1987). The difference in magnitude between the braking and propulsive force determine the resultant velocity of the runner; if the resultant force is negative the runner will decelerate (braking force > propulsive force), if it is positive the runner will accelerate (braking force < propulsive force) and if the two forces are equal the runner will maintain a constant speed (Miller, 1990; Toon, 2008). It is reported that, to maximise sprint velocity, braking force needs to be minimised with propulsive forces being maximised (Mero and Komi, 1986; Mero *et al.* 1992; Wood, 1987). Anteroposterior forces have been demonstrated to vary depending on classification of runner, as midfoot strikers have been found to produce a double peaked braking force, whereas, rearfoot strikers create a single peaked pattern (Cavanagh and LaFortune, 1980) as illustrated in Figure 5.6.

The vertical component of GRF has the largest magnitude of the three force components, typically in excess of 2.2 body weights (BW) when running at $4.5ms^{-1}$ (Cavanagh and LaFortune, 1980). For rearfoot and midfoot strikers the vertical component is typically bimodal in shape, as depicted in Figure 5.7. When discussing rearfoot strikers, the initial peak is referred to as the passive force peak or impact peak, with the second peak being termed as the active force peak (Nigg *et al,* 1983). There is a key difference between rear and midfoot strikers in the magnitude of the passive force peak, with rear foot strikers displaying a much larger and prominent passive peak when compared to midfoot strikers (Figure 5.7). Literature suggests that the vertical component of GRF is positively correlated with speed, as Nigg (1986) showed that as running speed doubled from $3m/s^{-1}$ to $6m/s^{-1}$ the impact force peak values increased from between 1300 N and 1400 N to between 2090 N and 2240 N.

The final component of GRF is the mediolateral force which identifies how the centre of mass of the body transfers from side to side during the stance phase. It has been identified as the smallest of the three components, with reported peak to peak amplitudes of 0.35 BW for midfoot strikers and 0.12 BW for rearfoot strikers (Cavanagh and LaFortune, 1980) and, perhaps for this reason, has been studied to a lesser extent.

Joint angular motion is another major factor in sprint performance and it has been identified that individual joint segment movement patterns vary according to locomotive speed. Guo *et al.* (2006) identified that changes in lower extremity joint angular motion as a result of increased velocity, resulted in increased stride length. As speed increases, it has been found that knee flexion decreases in the early stance phase, then significantly increases in the swing phase enabling longer strides to be taken. Ankle kinematics were also shown to be speed dependant with subjects demonstrating increased plantarflexion during push off allowing greater power production, and decreased dorsiflexion during the swing phase (Guo *et al.*, 2006).

The aim of this second stage of testing was to identify if wearing different pads causes a measurable difference in running kinematics, which could account for the negative effect on running performance not attributable to weight. Pad movement was also measured to help determine possible causes of changes in running kinematics.

5.2.1 Method

For this study, nine male county 1st and 2nd team players were used with a mean age of 20.2 years old (± 1.1 years). The nine subjects within this testing were different to those used within Stage 1; this was deemed acceptable due to the consistent trend demonstrated across the 10 subjects within Stage 1. Players were asked to perform six single runs for each of the five conditions outlined in the running time testing (NP, P1, P2, P3 and WC); again, condition order was randomised. The use of single runs rather than three consecutive runs was deemed acceptable as this study focused on the section of a run where the player is at maximal speed rather than accelerating/ decelerating, as Stage 1 identified this to be where cricket pads impede performance. However, to replicate the running pattern, in terms of accelerations and decelerations the players were asked to start from a stationary position and stop at a point 17.7m away from the start point. The start point was approximately 8m from the force plate such that the player would strike the force plate within their typical stride pattern (Figure 5.8). The exact start position was determined from trial runs and was recalculated for each condition. Three of the six runs were designed to obtain a left foot strike, the other three a right foot strike, by varying the lead foot/ leg at the start point. For all data captures the direction of locomotion was along the *x* axis of the force plate.

Motion data was collected using a four camera CX1 Coda system (Figure 5.9) sampling at 200Hz with two integrated Kistler 9281CA force plates, sampling at 1000Hz. The kinematic data was taken from the middle segment of the run between 6m and 10m with the force plate in the centre of this volume (Figure 5.10). Due to the protective equipment, a standard marker set up was not appropriate, as markers placed on the standard anatomical land marks at the knee and ankle would be covered by the leg guards, therefore, the CAST technique was used (Cappozzo *et al*, 2005). For the static trial, the marker positions were captured whilst the participant was standing in the centre of the capture volume with their arms raised so no markers were occluded; a redundant marker set of 32 active markers was used (Figure 5.11), which incorporated additional markers on both thighs, shanks and feet for the clusters (Table 5.1). The static trial was an essential procedure within the data collection process and was used to determine the relative position of the cluster markers to those placed on the anatomical landmarks, which are deemed as being representative of the joint centres. Once the static trial had been captured, two walking and running trials were completed again without leg guards to assess accuracy of the marker set up. The joint centre positions (Table 5.2) and joint angles (Figure 5.12) at the knee and ankle when calculated using the clusters were compared to those obtained using the markers on the knee and ankle. The difference between the two methods are outlined in Table 5.2, with a mean root mean square (RMS) of 1.64mm and 1.54mm across all subjects being found for the knee joint centre (KJC) and ankle joint centre (AJC) respectively. The maximum difference in knee angle between the cluster and anatomical marker placements was 3°, which is less than the amount of skin artefact identified by Reinschmidt *et al.* (1997), therefore, the CAST method was deemed appropriate. Once the static trial and accuracy tests were completed, markers that would be covered by the leg guards were removed; these included the medial and lateral knee and ankle markers for both legs. For the padded conditions, two additional markers were placed on each pad allowing the movement of the pad relative to the leg to be captured (Figure 5.13).

Marker	Definition	Position
L/RASI	Left anterior super iliac	Bony protrusion of the anterior superior iliac.
RASI	Right anterior super iliac	
LPSI	Left posterior super iliac	Dimples created by the posterior super iliac.
RPSI	Right posterior super iliac	
LTHAS	Left thigh anterior superior	Placed on the left and right thigh
RTHAS	Right thigh anterior superior	
LTHPS	Left thigh posterior superior	Placed on the thigh approximately 2 inches posteriorly to the LTHAS or RTHAS.
RTHPS	Right thigh superior	
LTHAI	Left thigh anterior inferior	Placed on the thigh, 1 inch below the L/ RTHAS and 2 inches forward of the line between L/ RTHIS and L/ RTHII.
RTHAI	Right thigh anterior inferior	
LTHPI	Left thigh posterior inferior	Placed on the thigh, 1 inch below the L/ RTHPS and 2 inches behind the L/ RTHAI and L/ RTHAI.
RTHPI	Right thigh posterior inferior	
LKNEL	Left knee Lateral	Along the flexion/ extension axis of rotation at the lateral femoral condyle.
RKNEL	Right knee lateral	
LKNEM	Left knee medial	Along the flexion/ extension axis of rotation at the medial femoral condyle.
RKNEM	Right knee medial	
LCALFS	Left calf superior	Placed 2 inches below the line between the L/RKNEL and the L/RKNEEM on the back of the calf.
RCALFS	Right calf superior	
LCALFA	Left calf inferior	Placed 5 inches directly below the L/RCALFS
RCALFA	Right calf inferior	
LANKL	Left ankle lateral	Along the flexion/ extension axis of rotation at the lateral Malleolus.
RANKL	Right ankle lateral	
LANKM	Left ankle medial	Along the flexion/ extension axis of rotation at the medial Malleolus.
RANKM	Right ankle medial	
LMTPL	Left metatarsal lateral	Dorsal aspect of the fifth metatarsal head.
RMTPL	Right metatarsal lateral	
LMTPM	Left metatarsal medial	Dorsal aspect of the first metatarsal head.
RMTPM	Right metatarsal medial	
LFTC	Left foot central	Placed directly 2 inches below the lateral Malleolus
RFTC	Right foot central	
LHL	Left heel	Placed on the back of the foot.
RHL	Right Heel	

Table 5. 1: Marker set and anatomical position, with redundant markers for static capture only in bold

Subject	KJC error RMS (mm)	AJC error RMS (mm)
1	1.08	1.36
2	2.14	1.13
3	1.03	1.97
4	2.45	1.23
5	1.37	1.74
6	1.77	1.49
7	2.26	1.73
8	1.75	1.33
9	1.05	1.89

Table 5. 2: Root mean square (RMS) difference in joint centre position at the knee joint centre (KJC) and ankle joint centre (AJC) when calculated using the knee and ankle landmarks and the cluster markers for all 9 subjects

The measurements taken from this study were stride parameters (stride width and length), kinematic data (knee and ankle joint angles (Cardan angles with a rotation sequence of *xyz)* and velocities, stance time, and stride frequency), GRF and pad rotation about the leg, allowing a biomechanical analysis of cricket leg guard influence on running movement and force generation, as well as determining the affect of pad movement on perceived comfort. Stride length was calculated as the distance between proximal end position of the foot at ipsilateral heel strike to the proximal end position of the foot at the next ipsilateral heel strike. The vector between these two points was then used in the calculation of stride width. The cross product of this vector with the position of the intermediate step gave the stride width i.e. the medio-lateral distance between proximal end position of the foot at ipsilateral heel strike to the proximal end position of the foot at the next contralateral heel strike. The GRF data was measured in terms of body weight (BW) which was calculated by dividing the force data by each participant's weight for the NP condition and dividing by their weight plus the weight of the pad or leg weight for the other conditions. This was to compensate for differences in subject and pad weight. The pad movement was calculated as a rotation about the leg axis, by determining the angle between two planes, which were defined by the KJC, AJC, lateral knee marker, lateral ankle marker and 2 pad markers, one of which was located at the centre of the knee area and one in the centre of the ankle area as illustrated in Figure 5.13. Plane 1 represented the leg and was identified from the lateral knee marker, knee joint centre and ankle joint centre. Plane 2, represented the pad and was identified from the knee joint centre, ankle joint centre and top pad marker. The angle between these two planes was calculated throughout the run, with average angle and standard deviation representing pad movement. The same calculations were used to calculate movement at the bottom of the pad utilising the lateral ankle marker rather than lateral knee marker for the leg, and the bottom pad marker rather than top marker for the pad.

Kinanthropometric data was also collected to analyse the fit of the pad, enabling a comparison between fit and performance to be made. The measurements taken were circumference and width of the leg without pads at the thigh (8cm above the top of the patella), knee (across the point of articulation) and calf (mid point between the knee and ankle). These measurements were also taken in each of the three padded conditions measuring the combined width and circumference of the leg and pad.

5.2.1.1 Subjective analysis

A subjective analysis was also performed on the pads; after all three pads had been worn players were asked to rank them in terms of perceived fit, restriction, pad movement and running impedance on a scale, as illustrated in Figure 5.14. A rank of 1 was given to the best fitting, least restrictive, least moving and least impeding pad.

5.2.1.2 Data processing

Once all the data had been captured, a 3D kinematic model was built using Visual 3D (version 4) software with the thigh cluster and foot cluster used to track movement of the knee and ankle joint centres (Figure 5.15).

5.2.1.3 Statistical analysis

Initially the knee and ankle data was analysed through the use of a cross correlation to determine if the movement pattern was consistent between trials and between subjects, with a high positive value (0.7-1) indicating a high degree of similarity between data sets. As with the running time data in stage 1 a Shapiro-wilks test was used to determine if the data was normally distribute. Providing the data was normally distributed a one-way repeated measures ANOVA with a post-hoc Tukey-Kramer test was completed to determine which results were significantly different ($p \leq 0.05$). A Gabriel comparison interval was used to illustrate where significant differences were identified between conditions (Gabriel, 1978).

5.2.2 Results

The kinematic and ground reaction force (GRF) data collected allowed a more in-depth study of the effect of cricket leg guards on running performance to be conducted. From the data, stride parameters such as width and length were investigated, as were the GRF forces in all three axes (anterior/posterior, medial/lateral and vertical). Once these parameters had been considered, kinematic data was used to determine if any changes in running technique were due to negative effects on running kinematics. Finally, to gain a further understanding of the interaction between the pad and the human, anthropometric measurements of the leg with and without pads were taken to determine if fit and size of the pad influenced the running motion.

5.2.2.1 Stride Parameters

As with the running time data, an ANOVA was performed on the results which revealed no significant differences between NP, P1, P2, and the WC ($p > 0.213$). P3, however, was found to significantly decrease stride length by 0.1 meters ($p = 0.01$) on average (Figure 5.16a) and increase the stride width of players by up to 0.12 meters ($p = 0.001$) (Figure 5.16b).

5.2.2.2 Ground Reaction Force

The GRF was measured for each completed run, allowing a comparison of anterior/posterior (x), medial/lateral (y), and vertical (z) forces between conditions. To assess if different pads affected the GRF, maximum force and impulse were measured (Hunter *et al.,* 2005). From the results it was apparent that all nine cricketers were midfoot strikers from the mediolateral and vertical GRF graphs depicted in Figure 5.17.

All nine participants had a double peaked breaking force as described in the literature as a typical characteristics associated with a midfoot striker (Cavanagh and LaFortune, 1980; Nigg *et al.,* 1983).

The anterior/posterior forces were used to determine if decreases in running speed could be attributed to larger braking forces and decreased propulsive forces whilst running in cricket pads. The ANOVA results showed that wearing cricket pads significantly (*F*=16.35, *p*=0.000) increased braking force by 0.1 BW, 0.09 BW, 0.3 BW and 0.1 BW for P1 (*p*=0.021), P2 (*p*=0.041), P3 (*p*=0.000) and the WC (*p*=0.038), respectively, when compared to the NP condition (Figure 18a). Maximum braking force was also significantly larger for P3 when compared to P1 (*p*=0.000), P2 (*p*=0.000) and the WC (*p*=0.000). As well as an increased maximum braking force, braking impulse also significantly increased (*F*=72.566, *p*= 0.000) for all padded conditions and the WC when compared to running in no pads, by 0.0061 BW.s, 0.0083 BW.s, 0.0163 BW.s and 0.0085 BW.s for P1 (*p*=0.000), P2 (*p*=0.000), P3 (*p*=0.000) and the WC (*p*=0.000) respectively (Figure 18b). As with maximum braking force, no significant differences were found between P1, P2, and the WC (*p*>0.082), whereas, P3 was found to significantly increase braking impulse when compared to all other conditions (*p*<0.001). When considering propulsive impulse, a significant difference between conditions was found (*F*=9.383, *p*=0.000), with the NP condition resulting in a significantly greater impulse when compared to the other conditions. P3 significantly reduced the propulsive impulse compared to NP (*p*=0.000), P1 (*p*=0.003), P2 (*p*=0.003) and WC (*p*=0.001), whereas, no significant differences were found in regards to maximum propulsive force (*F*=0.623, *p*=0.646) (Figure 18c and 18d). As a result, it was found that overall impulse was significantly lower in all padded and WC (*F*=70.436, *p*=0.000) conditions compared to the NP condition (Figure 19); P3 was also found to significantly decrease overall impulse compared to P1 (*p*=0.002), P2 (*p*=0.000) and the WC (*p*=0.000).

In terms of mediolateral forces, there were no significant differences between the NP and WC in terms of maximum force (*p*=0.342) or impulse (*p*=0.200), but, P1 and P2 significantly increased maximum force by 0.119 BW (*p*=0.000) and 0.091 BW (*p*=0.000) and impulse by 0.004 BW.s (*p*=0.000) and 0.005 BW.s (*p*=0.000) respectively when compared to the NP condition. As with maximum braking force, P3 was found to significantly increase maximum mediolateral force (p=0.000) and impulse (p=0.000) when compared to the other four conditions, with an increase in maximum force of 0.213 BW and impulse of 0.015 BW.s when compared to the NP condition (Figure 18e and 18f). Finally, within the vertical forces no significant differences were identified between the five conditions for maximum force (F=2.153, p=0.144) or impulse (F=0.798, p=0.528) (Figure 18g and 18h).

5.2.2.3 Kinematic analysis

The effect of cricket leg guards on running kinematics was assessed to determine if changes in stride parameters, GRF and effectively running speed were a result of restricted range of motion, resulting in changes in knee and ankle flexion and extension as well as joint angular velocities. Initially a cross correlation was performed on the mean data for each subject, where the data for all six repetitions were combined, with a value of 0 representing no correlation and a value of 1 representing a strong correlation. A strong correlation between subjects was identified, suggesting that there is limited variation between subjects (Table 5.3). Secondly a cross correlation was performed on the mean data between conditions which also illustrated a strong correlation (0.863 to 0.930) (Table 5.4) suggesting that there is considerable similarity between the joint angle data for all five conditions in terms of movement pattern, movement duration and degree of flexion and extension.

Figure 5.20 depicts joint angle data for subject 3's left knee and ankle, these results were deemed to be representative of all nine subjects' data, due to the high correlation shown between subjects. To determine if there were any significant differences in joint angles, the points of minimum and maximum flexion for the knee and ankle of each stride were considered; a one-way repeated measures ANOVA was used to determine if there were any significant differences between conditions (Figure 5.21). No significant differences ($0.533 \leq F \leq 1.878$, p>0.713) were found, suggesting that changes in stride parameters, GRF and running times are not as a result of changes in maximum flexion and extension of the knee or ankle.

Joint angle	Mean correlation	Standard deviation
Left knee angle	0.864	±0.013
Left ankle angle	0.818	±0.019
Right knee angle	0.823	±0.021
Right ankle angle	0.811	±0.018

Table 5. 3: : Mean cross-correlation results between subjects

Joint angle	Mean correlation	Standard deviation
Left knee angle	0.911	±0.009
Left ankle angle	0.863	±0.012
Right knee angle	0.893	±0.007
Right ankle angle	0.931	±0.012

Table 5. 4: Mean cross correlation results between conditions

Further analysis was completed on step frequency, stance time, angular velocity and running velocity (Table 5.5 and Figure 5.22). The results demonstrate significant differences in running velocity between conditions (F=1.436, p=0.001), with all padded and WC conditions found to significantly decrease running velocity when compared to the NP condition (p<0.01) (Table 5.5). No significant differences were found between P1, P2 and WC (p>0.317), however, P3 was found to have a significantly larger effect on running performance than all other conditions (p<0.01), supporting the results in Stage 1. The results demonstrate that although there is a significant difference in running velocity (p=0.001) there is no significant difference in peak angular velocities during ankle flexion (F=0.486, p=0.746) or knee flexion (F=0.657, p=0.894), ankle extension (F=0.274, p=0.894) or knee extension (F=0.387, p=0.816) (Figure 5.22). Further, no differences were found in step frequency (F=0.419, p=0.735), step time (F=0.237, p=0.914) or stance time (F=0.927, p=0.816). These results suggest that although cricket leg guards do significantly affect running speed, this is not a result of changes in knee and ankle joint kinematics or step frequency/ time.

Variable	Group Mean (±1SD)				
	NP	P1	P2	P3	WC
Step Frequency (Hz)	3.97 ± 0.27	3.89 ± 0.26	3.94 ± 0.26	3.87 ± 0.28	3.91 ± 0.29
Step time (s)	0.25 ± 0.02	0.26 ± 0.02	0.25 ± 0.02	0.26 ± 0.016	0.26 ± 0.02
Stance time (s)	0.17 ± 0.014	0.17 ± 0.013	0.16 ± 0.053	0.17 ± 0.025	0.17 ± 0.013
Velocity (m/s)	6.35 ± 0.15	6.13± 0.13	6.14 ± 0.18	6.01 ± 0.21	6.14 ± 0.20

Table 5. 5: : Kinematic data group means ± 1 standard deviation

5.2.2.4 Pad Movement

The results revealed relatively little pad movement across all three conditions, with a maximum rotation of 2.3° for any subject across all conditions. A strong mean correlation coefficient of 0.893 (±0.063) between repetitions of each condition was found for all nine subjects, as well as a mean correlation coefficient of 0.814 (±0.089) between subjects for all conditions. The high correlation found suggests that the pad movement is consistent over multiple runs and across different wearers. The results for Subject 4 are shown in Figure 5.23 as a representation of the overall findings. The results identify that for all three conditions, the average rotation from the original 90° position is less than 0.5°, with maximal rotation being less than or equal to 1° (Figure 5.23). No significant differences (p=0.571) between conditions were found, suggesting that perceived differences in pad movement are not a consequence of actual pad rotation whilst running.

5.2.2.5 Kinanthropometry

Six static measurements were taken for each condition, including width and circumference of the thigh, knee and calf. The results are shown in Figure 5.24 and were used to determine if there was a relationship between pad size and impedance. It was found that all three pads added a significant amount of size to the legs in terms of width and circumference at all three locations. The biggest changes in dimension were around the knee and calf for all three pads in respect to width and circumference. Overall, P3 added the greatest amount of bulk, increasing the width at the knee by 10.1cm compared to 7.4cm and 8.5cm on average for P1 and P2 respectively. These results suggest that the significant increase in stride width for P3 could be due to the added bulk in between the legs, preventing a natural running motion (as demonstrated in the NP condition) for P3 alone.

5.2.2.6 Subjective analysis

The subjective results collected throughout the testing allowed for a comparison between the cricketers' perceptions of the three pads and their actual affect on performance. The initial question focused on the perceived fit of the pad, with P1 and P2 consistently being identified as the best fitting pads (Figure 5.25a). A Friedman's test identified significant differences in perceived fit between the different pads, with the LSD_{rank} suggesting that both P1 and P2 are a significantly better fit than P3. When considering perceived restriction, P3 was also identified as the most restrictive pad with no significant differences between P1 and P2 (Figure 5.25b). With regards to pad movement, there was no significant difference found between P1 and P2 or between P2 and P3, however, P3 was perceived to move around the leg significantly more than P1 (Figure 5.25c). Finally, it was identified that P3 was perceived to impede running significantly more than P1 and P2. Players also perceived P1 as having a greater affect on their running performance than P2 (Figure 5.25d).

5.3 Discussion

It has been found that wearing cricket pads can have a negative effect on running performance and, contrary to Loock *et al's* (2006) findings, the magnitude of this effect is dependent on the type of pad being worn. Adding mass to the leg does affect running performance; however, other underlying factors clearly affect running speed. Certain pads, for example P3 in this study, can alter the natural running stride of the athlete causing them to shorten and widen their stride. This is particularly apparent when the added size to the leg forces an increase in natural stride width. Although there was an apparent change in stride kinematics, it was found that this was not as a result of restricted motion around the knee or ankle as the joint kinematics did not significantly alter between conditions.

GRF was also studied and the results suggest that, pads which cause an increase in stride width and decrease stride length also resulted in increased braking forces exerted on the body, resulting in a reduced overall impulse in the direction of locomotion, which, therefore, will decrease velocity. Associated with the decrease in anteroposterior impulse was an increase in mediolateral impulse suggesting that as stride width increases less force is applied in the direction of locomotion which contributes further to a lower resultant running speed. The combination of these results indicates that adding mass to the leg does have a significant effect on running speed and, therefore, to increase running performance the pad needs to be as light as possible. Other factors, such as the fit of the pads also appear to have an influence on performance. As an approximate guide, the size of the pad inside the leg needs to be minimised and kept below the width of the natural running stride as measured in the NP condition in order to minimise changes in running gait. The results suggest that minimising the effects on stride parameters and braking force, force generation in the direction of locomotion will be maximised and in turn reduce impedance caused by the pads. Pad movement was also assessed, using the angle between two planes to determine how much the pad rotates about the leg. A cross correlation identified that there was a strong correlation between both subjects and conditions. No significant differences in pad movement were found between conditions.

Alongside the objective results, subjective data was collected regarding perceived fit, restriction, running impedance and pad movement. A high degree of agreement was found between the subjective data and objective findings. P3 was rated as the worst fitting pad, which correlates with the dimensions of the pad when worn by the subjects. As shown in Figure 5.24, the additional width at the knee was significantly greater for P3 compared to P1 and P2. When considering perceived running impediment, there was agreement between the two sets of results although to a lesser extent, as P1 was correctly identified as having a lesser effect on running performance than P3, but was also identified as causing significantly more impedance than P2, which according to the running times data was not the case. In terms of actual and perceived pad movement there was no agreement between the two sets of results. No significant differences were found in the amount the pad moves about the leg, however, P3 was perceived to move significantly more than the other pads, suggesting further work is required regarding the interaction between the pad and the leg.

5.4 Summary

This study has measured and quantified the influence of cricket leg guards on running performance. Through the development of a procedure which allowed a biomechanical analysis of routine movements typically performed within the sport, further understanding of the degree of restriction provided by various leg guards and possible causes has been gained. The results suggest that all pads significantly hinder running performance when compared to running without PPE. In addition, significant variations in the degree of restriction between pads were discovered, which could not be solely attributed to the additional mass of the pads. A kinematic analysis revealed that certain pads significantly increase stride width and decrease stride length resulting in increased braking and mediolateral forces, without affecting joint kinematics. Pad movement was also assessed, with no significant differences between pads being identified, highlighting the need for further investigation of why different pads are perceived to move more than others. Comparing these results with static fit measurements, a common link between pad width and changes in stride parameters was ascertained, suggesting that the wider the pads are between the legs the more impedance will occur.

Chapter 6

Measurement of skin contact pressure under cricket leg guards

The hierarchical model discussed in Chapters 2 and 3 revealed that 'Fit' is a major factor in determining perceived comfort. Within 'Fit', pad movement and strap pressure were found to influence user comfort and satisfaction with the product. The work presented in Chapter 5 concluded that the 'Fit' of the pad does have a significant affect on performance in terms of running speed, however, the perception of different pads moving around the leg whilst running was not fully justified. Throughout the results presented thus far, another common finding has been the discomfort caused by areas of perceived high pressure, in particular, behind the straps. Therefore, the aim of this study was to identify relationships between areas of perceived discomfort and high pressure, as well as to determine if contact pressure variations during a stride contribute to the perception of pad movement.

6.1 Measurement of contact pressure

Garment design and fit play an important role in the sensation of pressure on the skin, which can have a significant influence on perceived comfort and greatly affects the desirability of an item of clothing or protective equipment (Sakaguchi *et al.* 2002). Pressure has been described as a maintained touch, which is experienced when an object is pressing on ones skin, resulting in a deformation (Hendrik *et al.*, 2008). In regards to skin pressure caused by a garment, it has been stated that the sensation experienced is closely related to the space between the body and the garment; if a garment's girth measurement is smaller than the body, either the garment will have to stretch or the body compress, resulting in a pressure being generated (Zhang *et* al., 2002). The skin has been found to be incredibly sensitive to pressure and can detect a displacement as small as 0.001mm in ideal conditions (Sciffman, 1995). Previous research has discovered that the pressure a garment applies to the skin is dependent on several variables including body shape, mechanical properties of the fabrics used, style and weight of the garment (Wong *et al.*, 2004). Searches have revealed there has not been any research published regarding the interaction between cricket leg guards and the skin; however, there is an abundance of literature within other fields, for example, brassier design and medical PPE (Miyatsuji *et al,* 2002). The results have identified the importance of minimising contact pressure and, as a result, deformation of the skin, when seeking to improve comfort (Acton *et al.*, 1976; Kyung and Nussbaum, 2007; Tsujisaki *et al*, 2004). High pressures not only cause discomfort but also physiological responses associated with the autonomic nervous system (Maruta and Tokura, 1988; Miyatsugi *et* al, 2002; Ogawa *et al*, 1979; Sone *et al,* 2000; Takagi, 1960), with high pressure brassier straps being found to reduce sweat rates and suppress saliva secretion when compared to low pressure straps. When relating these objective pressure results to subjective findings, it was found that areas of high pressure caused severe discomfort and pain (Miyatsuji *et al*, 2002) suggesting that, areas of high pressure need to be minimised to maximise comfort. Contact pressure has also been found to have a significant effect on the perceived fit of a garment, which has been identified as being a major contributor to perceived comfort.

A substantial amount of work has been conducted on skin contact pressure, with regards to comfort and end-user perceptions, across a wide variety of applications, from baseball hats (Kang, *et al,* 2007) to brassiers (Miyatsuji *et al,* 2002) as well as hand tools (Kuijt-Evers *et al,* 2007), using a variety of objective and subjective methods. Subjective methods used within various pressure studies have included questionnaires, rating scales and discomfort maps (Groenesteijn *et al.* 2004; Kong and Freivalds, 2003; Kilbom *et al.*, 1993). Although these methods can assist in developing designers understanding of end-users experiences, there are several limiting factors associated with these methods. For example, a large sample size is needed to gain a full understanding of the interaction between the subject and the item in question, which can make testing costly and time consuming (Lee *et al.*, 1993). Also the use of subjective methods alone can result in preconceptions and personal preferences being reflected in the data (Chen *et al,* 1994). Due to these limitations it has been recommended that objective and subjective methods are used together, allowing a fuller understanding to be gained.

In terms of objective measures, a variety of techniques have been used to predict end-user comfort including pressure sensors and numerical simulations (McGorry *et al*, 2003). Various pressure sensors have been used in previous studies, including load cells, miniature load cells, cantilever beams and strain gauges, and thin-film force sensors, allowing dynamic pressure measurements to be taken in real life situations (Makabe *et al.* 1991; Momota *et al.* 1994; Schmidt, 2007). However, there are several limitations associated with such methods, including sensor placement, which affects the accuracy and consistency of a measurement due to differences in anatomy between subjects (Wong *et al.,* 2004). Previous sensor technologies have limited results when considering the contact pressure of a large area. This was as a result of limitations in the number of sensing points, meaning as the sensor increased in size the area that each sensing point was covering was increased. Increasing the area covered by each sensing point could result in key factors being missed due to pressures being averaged over a larger area. To try and maximise consistency and overcome the need for subjects, 3D numerical modelling techniques have been used, which enable pressure distributions to be predicted on the basis of fabric properties. Although these methods have been found to decrease the cost of testing and demand on resources, they are static models, and therefore do not consider the affect of human movement on pressure (Wong *et al.*, 2004).

Sakaguchi *et al.* (2002) attempted to overcome issues with sensor technologies and 3D modelling techniques through the development of a new measurement technique, utilising a soft transparent rubber substitute for the human body, allowing existing products to be tested, without the need for subjects. Sakaguchi *et al* (2002) used the artificial limb to measure skin deformation; this was accomplished by shinning a light perpendicular to the skin surface of the substitute limb. As the light passed through the rubber, the deflection of the light was measured and used to determine skin deformation. If there was no deformation of the limb, the light shone perpendicular to the skin, whereas the deformed areas resulted in the light being reflected in a direction other than perpendicular, resulting in differences in brightness. Although this method was identified as a compromise between 3D modelling techniques and the use of pressure sensors on human subjects, allowing pressure measurements to be obtained over larger surface areas, it still does not take into account human movement.

As discussed, there are limitations with both objective and subjective measurements, therefore, it has been determined that both measurements need to be used when measuring comfort because of the complex nature of human sensory response to garment materials and their interaction with the skin (Kang *et al.* 2007). The combination of subjective and objective measures allows for a greater understanding of the relationship between design, materials, human sensitivity and comfort. The aim of this chapter is to develop an understanding of how the pad interacts with the leg both statically and dynamically, identifying correlations between areas of perceived discomfort and high pressure, also determining if variations in contact pressures whilst running contribute to perceptions of pad movement.

6.2 Sensor evaluation and selection

A major part of developing a suitable method for measuring skin contact pressure was determining which measurement system would enable the most accurate results to be collected, in terms of both a static and dynamic data collection. Previous studies have used a variety of techniques to measure contact pressure including load cells, strain gauges and thin-film force sensors (Ashruf, 2002; Bray *et al.* 1990; Schmidt, 2007; The Institute of Measurement and Control, 1998). Table 6.1 compares the different measurement types in terms of sensor flexibility, durability, resolution and accuracy (Schmidt, 2007).

From this analysis of different measurement techniques, it was determined that for measuring pressure on an irregular shape with a large contact area, for example the leg, thin-film force sensors would be most appropriate due to their flexible nature and high spatial resolution.

Sensor Type	Flexible	Spatial Resolution	Time-Resolved Measurements	Accuracy	Cost	Durability
Load Cell	No	Poor	Yes	High	Moderate	High
Miniature Load Cell	No	Moderate	Yes	High	Moderate	High
Cantilever Beams and Strain Gauges	No	Poor to Moderate	Yes	High to Moderate	Low	Moderate
Thin-Film Force Sensors	Yes	High	Yes	Moderate	Variable	Low to Moderate

Table 6. 1: Force sensor comparison based on the results of several studies (Schmidt, 2007; Ashruf, 2002; Bray et al. 1990; The Institute of Measurement and Control, 1998)

There are a variety of thin-film force sensors produced by different companies, all of which have differing characteristics to consider. Three main sensor technologies were considered - Tekscan, X-sensor and Novel. The specifications of the sensors are compared to the minimum required for this testing in Table 6.2. From this analysis, it was determined that the X-sensor would be the most appropriate measurement system for this analysis, due to excellent hysteresis and drift performance, whilst maintaining accuracy at the same level as the other types of sensors. Another advantage of the X-sensor is its ability to hold its calibration, enabling the entire testing to be completed without re-calibrating the sensor. The other two sensors require calibrating pre and post measurement, due to sensor instability (Schmidt, 2007). Another decisive factor was the number of sensing elements. With X-sensor it is possible to have up to 10,000 sensing elements per sensor, which allows good spatial resolution even for a large sensor. Texscan and Novel have a maximum of 1936 and 2048 sensing elements respectively, and as the sensor size increases the spatial resolution therefore decreases. The major limitation of the X-sensor is the low sampling rate that is a consequence of maximising the number of sensing elements to improve spatial resolution.

After comparing the different types of sensor, it was determined that an X-sensor pressure mat would be used within this testing, utilising a custom made LX200 sensor with dimensions of 50 cm by 40.6 cm (Figure 6.1). These dimensions were deemed suitable as it enabled the sensor to wrap around the majority of legs (up to 90th percentile) and map the pressure from the top of the foot to above the knee on the majority of wearers. The sensor had an operating pressure range of 1.4-150 kPa, incorporating 7000 sensing points with a resolution of 0.5 cm, which could be sampled at 15 Hz. The sampling rate was less than ideal, but a compromise had to be made, and as this would equate to between 12 and 14 samples per stride, it was considered to be adequate.

6.3 Contact pressure test methodology

6.3.1 Subjects

Nine university cricketers, playing at various levels from county first team to local club, all of whom were training at least once a week, and had good experience of wearing cricket leg guards, were recruited for this study. The participants had a mean age of 21.6 ±1.2 years.

6.3.2 Pad selection

Four pads currently available on the market were used (P1, P2, P3 and P4), varying in weight, design, construction and number of straps (Figure 2.2). These four pads were deemed to be a suitable representation of the current market as they had been identified as varying in terms of strap pressure and pad movement within Chapters 2 and 5. Within Chapter 2, P3 and P4 were identified as causing greater discomfort as a result of increased contact pressure than P1 and P2. Results from Chapter 5 also suggested that P3 is perceived to move about the leg significantly more than P1 and P2.

Feature	Minimum Requirement	XSensor	Tekscan (5101)	Novel
Sensor flexibility	Excellent	Excellent	Average	Excellent
Spatial Resolution	5 mm	From 2.5 mm	From 2.5 mm	From 5 mm
Accuracy	+/- 10%	+/- 10%	+/- 10%	+/- 10%
Sample Rate	25 Hz	Up to 68 Hz (dependant on sensor size)	150 Hz (500 Hz high speed)	400 hz
Hysteresis (percentage of full scale)	<5%	<2%	5%	<7%
Durability	Excess of 10,000 measurements	>100,000	Up to 1000	>100,000
Drift	<5% per 15 min	<5% over 1 hour	15% over 1 min	7.6% over 1 min
Pressure Range	1.4-140 kPa	Up to 1.4-150 kPa	0-517 kPa	0-13,789 kPa
Calibration	Once per 100 cycles	Once per 100,000 cycles	Pre and post cycle	Pre and post cycle
Sensing area	300 mm x 400 mm	Up to 810 mm x 2100 mm	Up to 340 mm x 149 mm	Up to 506 mm x 506 mm
Number of sensors	5000	Up to 10,000	1936	Up to 2048
Thickness	2.5 mm	1.04 mm	0.1 mm	2 mm
Temperature range	10-40°C	10-40°C	-9-69°C	10-40°C
Humidity	5-90%	5-90%	5-90%	5-90%
Compatible with Matlab	Yes	Yes	Yes	Yes

Table 6. 2: Comparison of three different types of thin-filmed pressure sensors

6.3.3 Objective measurement protocol

Each participant was required to complete one static and two dynamic measurements on a treadmill, whilst wearing the X-sensor mat under each set of pads. The treadmill used was a HP Cosmos Saturn (Figure 6.3); this treadmill was deemed suitable due to its wider running belt (1.25m wide) that would allow the subjects to naturally increase their stride width, if necessary, due to the cricket pads. The treadmill was fitted with handrails and a harness to allow participants to safely stop the test at any point if necessary. To determine a suitable treadmill speed, the players were asked to run at approximately 80% of their maximum intensity, whilst wearing their own pads, to prevent any augmentation or pre-judgements being made prior to the test commencing. This resulted in all trials being conducted at running speeds ranging from 5.2m/s to 7.3m/s.

The pressure sensor was wrapped around the leading leg of the player (left leg for right handed batsmen and right leg for left handed batsmen) and secured in place to the bare leg with 3M hypoallergenic double sided tape, so that the sensor covered an area from the top of the shoe to above the knee. All participants wore shorts throughout the testing to prevent variations and creases in trouser material affecting the pressure data. The sensor was wrapped around the leg ensuring that the sensor overlap was located under the buckle on the lateral side of the pad, so that the sensing area covered the entire circumference of the leg. Creases in the sensor were kept to a minimum under the pad and strap regions to maximise measurement accuracy (Figure 6.4). Once the sensor was in place, the data acquisition box and port were fastened to the lateral side of the thigh through the use of elasticated straps, and all cables passed through the harness to ensure that they did not interfere with the running stride. All players fastened the pad to the leg themselves, at their preferred tightness, to allow the results to reflect the contact pressures the players would experience if wearing the pads whilst playing. The order in which the pads were worn was randomised for each participant to prevent any order effects. The pressure sensor was also used to trigger a Photron Fastcam high speed camera (Figure 6.2), capturing at 125 frames per second, to enable pressure measurements to be synchronised with the stride motion.

A static measurement was recorded initially with the participant standing still for 5 seconds. The static measurement was taken to assess the fit of the pad prior to running, whilst the leg was straight. Two dynamic measurements were then captured with 2 minutes rest between each trial. The participants were asked to run at their designated speed (as previously set) for ten strides, whilst pressure and video data was captured.

After all three measurements had been captured; the participants had 5 minutes rest before testing recommenced with the next pad, to help prevent fatigue. All methods used within this testing were approved by the Loughborough University ethical committee prior to testing.

6.3.4 Subjective measurement protocol

Throughout the testing, a questionnaire was completed by all participants (Appendix 6). Initially, they were asked for their first impressions of each of the four pads prior to running in them. This section of the questionnaire was completed after the static trial, but prior to the two dynamic trials. Within this first section, an open ended question was used to record location and cause of any initial discomfort or dislikes. The second section of the questionnaire was completed post use and recorded the subjects final assessment of the pad, using, rating scales for pad width and length (Figure 6.5), and an open ended question, as used within section one, to record the location and cause of any discomfort. This section also asked participants to identify any sources of perceived restriction on an image of the pad. The final section was completed once all four pads had been assessed; the players were asked to rank the pads in terms of comfort, strap pressure, fit, and pad movement on a continuous scale, as illustrated in Figure 6.6. This final section was included to enable relationships between end-user perceptions and objective measurements to be analysed.

6.3.5 Data processing and analysis

The dynamic data was processed in three stages. Firstly, the video data and pressure data were synchronised allowing the data to be separated into ten individual strides within each data capture. The data was then separated into different sub-stages of the running stride, from ipsilateral heel strike to contralateral toe off, identifying front foot heel strike (FFHS), front foot toe off (FFTO), back foot heel strike (BFHS) and back foot toe off (BFTO). Finally, the data was separated into different regions (pad, top strap, middle strap and bottom strap). The location of each region was determined visually by the outline depicted on the X-sensor pressure map and the position in relation to the edge of the sensor, which was always positioned under the buckles of the pad. The size and area of each pad was compared to the actual pad to validate the dimensions and the size of each region was kept constant during the analysis of different data sets.

Initially, a qualitative analysis was conducted on both the static and dynamic data. This was done by overlaying the pressure map on an image of the corresponding pad, as depicted in Figures 6.7 and 6.10-6.13A. Then a more in-depth objective analysis was conducted studying contact area, peak pressure and mean pressure for all four regions (parts A-C of Figure 6.8 and parts B-D of Figures 6.10-6.13). The contact area represented the total area under each region where a pressure greater than 1.4 kPa was being measured. The peak pressure represented the maximum pressure measured at any one sensing point within each region, and average pressure was the mean pressure over the contact area. It was determined that both peak and average pressure should be studied, as the peak pressure allowed the maximum pressure exerted on the leg to be identified, however, it only represents a single sensel within the area and the sensel at the highest pressure could vary from frame to frame. It is therefore more sensitive to measurement error. The average pressure data is based on more data and gives more reliable results, however, small localised areas of extremely high pressure will have less influence on the average data, which could result in areas of significant importance going unnoticed.

6.3.5.1 Statistical analysis

To determine if there were differences in pressure profiles between strides and subjects, each capture was separated into 20 separate strides (10 strides from trial one and 10 from trial 2) for each condition, and each stride considered as a percentage of cycle completion to overcome differences in stride duration between subjects and align data. Peak pressure, average pressure and contact area were studied at each of the four regions previously determined (pad, top strap, middle strap and bottom strap). Once the data had been separated into individual strides, a cross correlation was utilised to determine if there was a significant difference in movement pattern, giving a value between -1 and 1, with a higher value indicating a strong positive correlation. To determine if the data was normally distributed a Shapiro-Wilk test was performed on the objective data. Once data had been found to be normally distributed ($p>0.05$), a one-way repeated measures ANOVA was used to determine if there was a main effect between conditions, secondly a Tukey-Kramer post-hoc test was completed to determine which results were significantly different ($p\leq0.05$).

6.4 Contact pressure results

6.4.1 Static results

The static measurements were taken immediately after the pads were fixed in place by the players, whilst the subject stood stationary on the treadmill. The results from these measurements are illustrated in Figures 6.7 and 6.8 and were used to determine if differences in pad and strap pressures were as a result of differences in fit or whether they are only present whilst the player was in motion. The results of the static measurement suggest that there were significant differences in contact area between the four padded conditions ($p=0.000$). P2 was found to have a significantly greater contact area in comparison to the other three pads. Increasing contact area by 42cm^2 ($p=0.01$), 90cm^2 ($p=0.000$), and 84cm^2 ($p=0.000$) when compared to P1, P3 and P4 respectively (Figure 6.8b). There were differences in the size of the pads with P2 having the largest surface area (1220cm^2), with 17.3% of the total surface area applying a pressure greater than 1.4kPa to the leg, compared to 15.3%, 10.7% and 11.0% for P1, P3 and P4 respectively. P1 was also found to have a significantly greater contact area than both P3 ($p=0.01$) and P4 ($p=0.01$), which had similar contact areas. In terms of strap contact area, the top strap of P1 was found to have a significantly greater contact area than P3 ($p=0.02$) and P4 ($p=0.02$), between which there was no significant difference ($p=0.492$). For both the middle and bottom straps, P1, P3 and P4 were found not to vary significantly, whereas the contact area under the middle strap of P2 was significantly less ($p=0.001$).

Regarding peak pressures, no significant differences were found between the four conditions under the padded area (*p*=0.351) (Figure 6.8d), whereas P3 (*p*=0.01) and P4 (*p*=0.01) were both found to apply significantly greater pressure under the top strap compared to P1. With P2 not having a top strap these high pressures of up to 57.2 kPa were not applied to the leg. Under both the middle and bottom straps, P1 and P2 applied significantly less pressure to the leg than P3 ($p<0.01$) and P4 ($p<0.01$), with no significant differences being found between P1 and P2 ($p>0.457$) or P3 and P4 ($p>0.261$). Finally average pressure under each region was considered. Pads P1 and P2 were found to apply significantly less pressure to the leg under the padded region, compared to P3 (*p*=0.001) and P4 (*p*=0.001), which did not vary significantly (*p*=0.297). In regards to the straps, there were no significant differences measured between any of the four conditions (*p*=0.371). Between subject variation was also analysed; with no significant difference being found between subjects for any of the conditions ($p>0.278$) or individual regions ($p>0.317$), despite the players attaching the pad at their preferred tightness.

6.4.2 *Dynamic test results*

The dynamic data included two repetitions of ten strides per condition per subject, resulting in large amounts of data. The initial analysis was aimed at determining if the pressure profiles varied significantly between individual strides for each condition and between participants. The cross-correlation results identified there was a strong correlation between the separate strides for all four regions in regards to peak pressure (0.835 to 0.999), average pressure (0.838 to 0.999) and contact area (0.806 to 0.999), across all four conditions (Table 6.3 to 6.5). Therefore, a mean pressure profile for each condition was calculated for all nine subjects, allowing a between subjects and conditions analysis to be conducted. The results indicated a high degree of consistency between subjects, as can be seen by the limited variation between the means for each subject, illustrated by the results for average pressure under the pad in Figure 6.9. Therefore, it was deemed appropriate to discuss the results as a whole rather than on an individual subject basis. However, when discussing the pressure maps for each pad, the data for Subject 5 will be presented as it was deemed representative of the other results, as it contained the same trends as can be seen in all nine subjects' data.

Analysis of the pressure maps revealed several interesting features regarding the way each pad interacts with the leg. The pressure exerted on the leg by P1 (Figure 6.10) under the pad region maintained a consistent location throughout the running stride, with the majority of pressure being exerted down the centre of the pad. Although the location of the pressure was consistent the contact area did appear to vary, gradually decreasing in size during the swing phase. A substantial increase in pressure was apparent from 20% to 60% of the stride in the centre of the shin area. In regards to strap pressure, both the middle and bottom straps appear to maintain a relatively consistent pressure and contact area throughout, however, a substantial increase in peak pressure under the top strap can be seen during the swing phase, as the leg reaches maximum flexion (60-75%). The contact area of P2 appears to be larger than P1, with a more even distribution of pressure across the entire pad (Figure 6.11), rather than just down the centre. The location and size of the pressure appeared to be more consistent than P1. Subtle increases in strap contact pressure can be seen but are not to the magnitude of those found under the top strap of P1. The contact area of P3 (Figure 6.12) was much smaller than that found for P1 and P2, with large variations in regards to size and location. Throughout the entire stride, the location of the pressure applied to the leg varies from the medial side of the pad (1%) to the lateral side (60%) before returning to the original position (90%). As with P1, a substantial increase in peak pressure under the top strap occurred at the point of maximum flexion. The middle strap displayed minimal variation in terms of contact area and magnitude of pressure, whereas a substantial increase in pressure throughout the stance phase was found under the bottom strap. P4 demonstrated similar results to P3 with the contact pressure varying in both location and size (Figure 6.13). As with P1 and P2 there was a change in the magnitude of pressure exerted under the pad during the stance phase, however, it was not as large an increase as with the other pads. Throughout the running stride, contact pressure under the middle and bottom strap did not appear to vary significantly, whereas the top strap demonstrated a significant increase in contact pressure at the point of maximal flexion, as was described for P1 and P3.

	P1				P2			P3				P4			
Subject	Pad	Top strap	Middle strap	Bottom strap	Pad	Middle strap	Bottom strap	Pad	Top strap	Middle strap	Bottom strap	Pad	Top strap	Middle strap	Bottom strap
1	0.998	0.988	0.998	0.991	0.983	0.962	0.880	0.897	0.942	0.986	0.896	0.992	0.953	0.970	0.975
2	0.996	0.946	0.977	0.988	0.997	0.963	0.977	0.989	0.862	0.988	0.917	0.996	0.874	0.993	0.938
3	0.985	0.954	0.991	0.879	0.955	0.806	0.926	0.979	0.832	0.975	0.839	0.951	0.858	0.979	0.851
4	0.960	0.935	0.934	0.930	0.929	0.925	0.929	0.926	0.918	0.930	0.920	0.930	0.916	0.940	0.894
5	0.999	0.982	0.998	0.991	0.986	0.997	0.942	0.986	0.974	0.967	0.985	0.980	0.968	0.984	0.997
6	0.979	0.959	0.966	0.961	0.958	0.961	0.935	0.956	0.946	0.948	0.952	0.955	0.942	0.962	0.946
7	0.972	0.959	0.963	0.942	0.936	0.930	0.922	0.936	0.917	0.943	0.920	0.946	0.929	0.933	0.938
8	0.971	0.959	0.963	0.946	0.944	0.946	0.937	0.944	0.926	0.948	0.928	0.947	0.933	0.939	0.941
9	0.970	0.957	0.956	0.940	0.938	0.939	0.938	0.945	0.932	0.944	0.933	0.947	0.936	0.941	0.941

Table 6. 3: Cross-correlation results for the comparison of individual strides in terms of contact area

	P1				P2			P3				P4			
Subject	Pad	Top strap	Middle strap	Bottom strap	Pad	Middle strap	Bottom strap	Pad	Top strap	Middle strap	Bottom strap	Pad	Top strap	Middle strap	Bottom strap
1	0.995	0.990	0.997	0.999	0.965	0.962	0.938	0.995	0.908	0.983	0.993	0.999	0.913	0.905	0.992
2	0.997	0.977	0.968	0.997	0.985	0.970	0.983	0.980	0.864	0.982	0.951	0.992	0.839	0.994	0.974
3	0.994	0.944	0.993	0.925	0.991	0.993	0.849	0.935	0.873	0.994	0.835	0.975	0.851	0.986	0.972
4	0.966	0.949	0.948	0.945	0.944	0.940	0.935	0.937	0.934	0.945	0.937	0.948	0.936	0.981	0.973
5	0.974	0.995	0.986	0.998	0.990	0.995	0.991	0.984	0.928	0.988	0.991	0.989	0.934	0.995	0.993
6	0.970	0.972	0.967	0.972	0.967	0.967	0.963	0.961	0.931	0.967	0.964	0.969	0.935	0.988	0.983
7	0.976	0.969	0.971	0.968	0.955	0.951	0.928	0.944	0.933	0.961	0.931	0.943	0.943	0.940	0.952
8	0.974	0.969	0.972	0.973	0.964	0.958	0.933	0.945	0.935	0.961	0.931	0.952	0.952	0.946	0.958
9	0.972	0.966	0.969	0.969	0.960	0.954	0.935	0.948	0.941	0.959	0.939	0.957	0.960	0.951	0.963

Table 6. 4: Cross-correlation results for comparison of individual strides for peak pressure

	P1				P2			P3				P4			
Subject	Pad	Top strap	Middle strap	Bottom strap	Pad	Middle strap	Bottom strap	Pad	Top strap	Middle strap	Bottom strap	Pad	Top strap	Middle strap	Bottom strap
1	0.999	0.989	0.998	0.996	0.982	0.976	0.974	0.996	0.942	0.988	0.984	0.998	0.935	0.985	0.990
2	0.995	0.968	0.987	0.995	0.995	0.980	0.983	0.996	0.854	0.992	0.970	0.998	0.887	0.994	0.981
3	0.993	0.953	0.985	0.942	0.992	0.961	0.838	0.982	0.914	0.981	0.876	0.997	0.857	0.986	0.954
4	0.977	0.957	0.957	0.954	0.953	0.949	0.947	0.951	0.946	0.956	0.950	0.957	0.943	0.979	0.968
5	0.994	0.997	0.997	0.998	0.996	0.994	0.993	0.986	0.990	0.985	0.967	0.995	0.985	0.987	0.985
6	0.986	0.977	0.977	0.976	0.974	0.972	0.970	0.969	0.968	0.970	0.958	0.976	0.964	0.983	0.976
7	0.980	0.973	0.978	0.973	0.961	0.961	0.944	0.958	0.946	0.971	0.946	0.960	0.955	0.956	0.963
8	0.980	0.974	0.979	0.976	0.965	0.963	0.948	0.961	0.948	0.969	0.948	0.964	0.959	0.958	0.966
9	0.979	0.973	0.975	0.972	0.962	0.959	0.954	0.966	0.955	0.964	0.952	0.967	0.964	0.960	0.968

Table 6. 5: Cross-correlation results for comparison of individual strides for average pressure

Once a visual inspection of the pressure maps had been conducted a more in-depth objective assessment was completed. Initially, the interaction between the padded region and the leg was studied, with a particular focus on contact area, average pressure and peak pressure. Again, P2 was found to have the largest and most consistent contact area (Figure 6.14), with a mean area of 212.8 ±10.1 cm^2 (17.4 ±0.8% of total surface area), compared to P1, P3 and P4 which were all found to have significantly smaller contact areas with larger variations during the stride of 166.7 ±16.2 cm^2 (15.9 ±1.65% of total surface area), 129.3 ±23.9 cm^2 (12.5 ±2.31% of total surface area) and 123.1 ±20.3 cm^2 (11.3 ±1.86% of total surface area) respectively (Figure 6.14 and 6.15).

Significant changes in peak pressure under the padded region were found (Figure 6.16); however, average pressure over the area in contact with the leg did not change accordingly for any of the four pads. These results suggest that there are very localised areas of high pressure, however, when considering the entire region there is not a significant difference, demonstrating the need to consider both peak and average pressures. In terms of peak pressure, a consistent trend can be seen for P1, P3 and P4, where a sudden increase in peak pressure occurs between BFIC and BFTO (Figure 6.16). This stage in the gait cycle was where the front leg reached maximum flexion (Figure 5.20a), with the areas of high pressure being located at the same position that the straps are attached to the pad, with particular reference to the top strap. Although all three pads demonstrated a significant increase in pad pressure, there were substantial differences in maximum pressure, with P1 reaching peak pressures of 67.4 ±3.9kPa, compared to 79.6 ±4.6kPa and 80.8 ±4.0kPa for P3 and P4 respectively.

The second area of interest was the top strap, which was identified as a major source of discomfort in terms of pressure within all of the testing chapters thus far. As previously mentioned, it was found that there was a significant increase in peak pressure under the top strap from just prior to BFIC to BFTO (swing phase of the instrumented leg) for P1, P3 and P4 (Figure 6.17). For P1 a dramatic increase in strap pressure was measured at the point of maximum flexion reaching 101.9 kPa (±7.3 kPa) on average. This sudden increase in peak pressure was also found for P3 and P4 which reached peak pressures of 133.2kPa (±5.0 kPa) and 141.3 kPa (±3.5 kPa) respectively. As P2 is of a two strap design it was not subject to these extreme pressures found behind the knee. Unlike changes in pad pressure, these increases corresponded to significant increases in average pressure over the contact area (Figure 6.18), despite the contact area for P1 and P4 increasing and P3 remaining relatively constant (Figures 6.10-6.13b). Although these findings were consistent for all nine subjects there was a discrepancy in timing of the peak pressures for P1, with four subjects reaching their peak pressure approximately 10% earlier in the gait cycle. This misalignment of peak forces could be as a result of the relatively slow sampling frequency of the X-sensor. From the pressure maps (Figures 6.10a to 6.13a) it can be seen that the areas of high pressure are localised to two very specific areas, with other areas of the strap maintaining a lower pressure, closer to those experienced throughout the rest of the gait cycle. For all three pads which have a top strap, the extreme high pressure is consistently located over the area where the semi-tendinosus and semi-membranous tendons protrude whilst knee flexion occurs (Figure 6.10a to 6.13a).

The middle strap region for all four pads remained substantially more stable within each condition, in regards to contact area, peak pressure and average pressure (Figures 6.10-6.13), as discussed in the qualitative analysis. Peak and average pressures were significantly lower than under the top strap, with no sudden increases or decreases in pressure as a result of gait cycle position. There were no significant differences found between conditions in terms of peak (p=0.679) or average pressure (p=0.473), however, P2 was found to have a significantly lower contact area of 24.9 ±2.8 cm^2 (p<0.001), compared to 80.5 ±6.7 cm^2, 72.3 ±15.1 cm^2 and 71.1 ±9.0 cm^2 for P1, P3 and P4 respectively (Figure 6.19).

The final region to be studied was the bottom strap, which typically sits below the belly of the calf muscle and at the top of the Achilles tendon. For P2 and P4, the contact area of the bottom strap shows minimal variation throughout the gait cycle, with average contact areas of 10.39 ±1.6 cm^2 and 35.8 ±4.3 cm^2 (Figure 6.20). As with the middle strap, P2 was found to have a significantly lower contact area than the other three pads (p=0.000). P1 demonstrates more variation than P2 within the gait cycle, as contact area starts to decrease just after FFIC (10%) maintaining this decreased area until just before BFTO (80%) (Figure 6.20). P3 was found to have the greatest variation in contact area, as it was found to have a sudden decrease in contact area, dropping from 51.3 cm^2 to 39.8 cm^2 on average between FFTO and BFIC. This sudden decrease in contact area could be as a result of the ankle flexing as the front leg is brought through (Figure 5.20b), resulting in the bottom of the pad being compressed against the leg, releasing pressure under the bottom strap. The pressure map for P3 supports this, as an increased area of high pressure can be seen on the pad around the area that the bottom strap is attached (Figure 6.12a), suggesting the pad is pressing into the leg at this area to a greater extent. The peak pressure data showed variation throughout the running stride for all four conditions. The change in bottom strap peak pressure throughout the running stride varied between conditions. P1 demonstrated a reduction in peak pressure of 9.73 ±2.14 kPa between 10% and 60% of the gait cycle. P2 demonstrated an increase of 11.29 ±2.83 kPa between FFIC and FFTO, followed by a gradual decrease, returning to the levels experienced at FFIC, between BFIC and BFTO. P3 demonstrated a sudden increase in peak pressure of 4.64 ±1.68 kPa between FFTO and BFIC. Finally P4 also demonstrated a sudden increase in peak pressure at BFIC of 14.13 ±3.22 kPa. However, no significant differences in peak pressure were identified between conditions (p=0.194). P1 and P3 demonstrate a constant average pressure, whereas P2 was found to increase pressure during FFTO, despite no variation in contact area or peak pressure, suggesting more of the contact area reaches the upper limits of the pressure applied by the bottom strap, this is illustrated within the pressure map for P2 (Figure 6.11). P3 was also found to have a significantly higher average pressure under the bottom strap than the other three pads (p<0.01) (Figure 6.21).

6.4.2.1 Subjective responses

The questionnaire used to assess subjective responses enabled the end-users' perceptions of the pads to be assessed in regards to their initial perceptions of the pads, post use opinions, as well as recording any areas of significant discomfort. The initial assessment of the pad was incorporated to help determine the end-users instant perception of the pad was when they wore it for the first time, in terms of fit and contact pressure. The final assessment was used to determine if the perception of pads had changed during use. The results from both assessments were found to be consistent, suggesting that the initial sources of discomfort remained a factor throughout use and will, therefore, be discussed together. Within the two pad assessments (initial and final), P2 stimulated the most positive responses in terms of fit of the pad, with seven respondents referring to how well the pad fits the leg (Table 6.6). This was reflected within the pad width and length assessments (Figures 6.22 and 6.23) where P2 was identified to be of ideal width and length, six and five times respectively. Other positive connotations between the fit and reduced restriction were made, all be it with less frequency. However, P2 was perceived to have some less desirable features including the rigidity of the pad, with specific comments referring to the way the pad digs into the knee and thigh due to its lack of flexibility. P1 was also found to have some desirable features although to a lesser extent than P2, with particular reference to how the pad moulds to the leg and the material of the straps, although, these positive features did appear to be due to more personal preference rather than a reflection of the majority of subjects. In terms of negative perceptions, there was a general consensus that the pad was slightly bulky and needed to be longer amongst other things, however, the strength of agreement between different subjects was substantially less than for comments regarding P2. This was reflected within the results regarding perceived width as P1 had a greater degree of variation in terms of the perceived size of the pad, with an equal split between participants in terms of the width of the pad, with half of the sample identifying it to be of ideal width and the other half finding it to be too wide. The majority of players found P1 to be of ideal length (Figure 6.22 and 6.23).

The results highlighted a common dislike for the top strap design of P3 and P4, with a very strong consensus between the subjects stating that the top strap caused a high degree of discomfort behind the knee. Related to this dislike for the pressure applied behind the knee, three subjects also commented that the coarseness of the material used for the top strap caused discomfort. The majority of participants stated that both P3 and P4 are too wide, with all nine respondents identifying P3 as being too wide and eight respondents identifying P4 as too wide or much to wide in the assessment of perceived width (Figure 6.22). Although the majority of comments for P3 were of a negative nature, there were some positive comments made regarding the length of the pad, with six respondents identifying the pad to be of ideal length (Figure 6.23). P4 however, does not receive any positive comments regarding the design of the pad suggesting the subjects were generally dissatisfied with the pad itself.

Pad 1	**Pad 2**	**Pad 3**	**Pad 4**
Pad feels slightly bulky. (1,2,3,5,6)	Well fitted so not bulky (1,2,3,7)	Top strap digs in behind the knee. (1,2,3,4,6,7,9)	Material of the top strap is rough. (1,3,5)
Overall relatively comfortable (1)	Feel a lot less restrictive between the legs. (2,7,9)	Pad is very wide around the knee. (1,2,4,7,8)	Top strap digs in behind knee. (2,4,5,6,7,8,9)
Pad feels snug. (1)	Top of pad digs into the thigh when standing straight legged. (1,3,6,8)	Feels wide on the thigh. (2,5)	Pad feels wide. (1,4,5)
Very good straps, material feels good. (2,8)	Pad digs into the knee. (4,3,8)	Pad does not feel secure to the leg. (3)	Restrictive behind the knees. (2,7,8)
Top strap digs in a little. (3,4,9)	Very rigid (4,5)	Pad is very bulky. (2,4)	Pad feels long. (4)
Pad feels short. (4)	Feel short. (5)	Good length (1,5,6,9)	Very inflexible. (4)
Does not sit on the foot well. (5)	Straps too short (6)	Digs into foot. (7,9)	Tight fit around the ankle (5)
Straps to short. (6)			Dig into foot (7, 6)

Table 6. 6: Compilation of the nine subjects' initial and final assessment results of each of the four pads, subject numbers are in brackets

6.4.2.2 *Areas of discomfort*

Figure 6.24 depicts the areas of each pad which were specifically identified as causing severe discomfort and the amount of agreement shown between participants. The results suggest that, on the whole, P1 and P2 were perceived to be the more comfortable pads with fewer regions of discomfort identified and with less frequency for P1, two main areas of discomfort, the top strap and the inside of the knee were identified by four participants as areas of discomfort. The foot arch was also identified as an area of discomfort by two participants. Out of these four areas, the top strap was the only area of discomfort relating to contact pressure. Only one major area of discomfort was highlighted for P2 which was the top of the pad which was mentioned in both initial and final assessments, with six participants highlighting this area as causing significant discomfort. P3 appears to have caused more discomfort than P1 and P2 with six areas identified as major causes of discomfort by three or more respondents. The top strap, knee roll and inside edge of the pad all caused discomfort to at least six respondents. Only two of the areas identified were related to contact pressure (top and bottom strap), with the other regions being as a result of their affect on the running stride. P4 received similar responses to P3 with five areas identified by a minimum of four participants as causing discomfort, including the knee roll, top strap and inside edge of the pad as was found to be the case with P3.

6.4.2.3 *Rank orders*

The rank order results were analysed through the use of a Friedman's test as described in Chapter 3. For all questions, the Friedman's *T* statistic revealed significant differences between the conditions ($p<0.05$), as it was greater than the Chi-square value of 11.3 (for $k=4$ at a significance level of 0.01). To identify which conditions were perceived to be significantly different in regards to comfort, strap pressure, fit, weight, pad movement, and ease of running the statistical method of Fisher's LSD_{rank} was used, with a lower rank sum indicating the pads were more comfortable, of better fit, moved less and applied lower strap pressure. For overall comfort, there were no perceived differences between P1 and P2, or between P1, P3 and P4, however, P2 was perceived to be significantly more comfortable than P3 and P4 (p<0.01) (Figure 6.25). P1 and P2 were ranked as a significantly better fit than P3 and P4 (p<0.05) (Figure 6.25). This was also the case with perceived strap pressure where no significant difference was identified between P1 and P2, but these two pads were perceived to out perform P3 and P4. When considering degree to which the pad moves whilst running, P2 was perceived to move significantly less than the other three conditions (p<0.05). P1 was also perceived to move about the leg significantly less than P3 and P4 (p=<0.05) (Figure 6.25).

6.5 Discussion

From the results, it can be seen that the way in which the pad applies pressure to the leg does not vary significantly between players or from stride to stride; whereas, distinct differences in static and dynamic contact pressures were found between pads. Significant differences were found between the four conditions in terms of contact area and pressure applied to the leg and these differences can be related to perceived comfort. P2, which was the only pad of a moulded design, was found to have the largest and most consistent contact area. Within the subjective results P2 was identified as the best fitting pad, as well as the pad which moved about the leg the least. The shape of P2 also allowed the contact pressure to be distributed evenly around the leg, whereas for P1, P3 and P4, more localised pressures were applied. Pressure was primarily located down the centre of the pad for P1, whereas for P3 and P4 the pressure was more down one side. Throughout the running stride, the pressure applied to the leg by P3 and P4 varied significantly in terms of location and contact area, certainly more so than for P1 and P2, this may be the reason why P3 and P4 were perceived to move about the leg significantly more than P1 and P2.

The magnitude of pressure applied to the leg in terms of average and peak pressure were also considered. In terms of average pressure under the pad region, there were no significant differences found between conditions. Peak pressures, however, did increase for P1, P3 and P4 at BFIC, but this was not commented on within the subjective results, suggesting that although there is an increase in pressure, it is not at a high enough level to cause discomfort. There was also a discrepancy between the objective and subjective results for P2. The top of the pad was identified as a major source of discomfort, as a result of it 'digging' into the leg, but no increase in pressure in that region was measured.

P1, P3 and P4 were all identified as causing discomfort under the top strap. These results were supported within the objective data where the highest pressures were consistently found under this region, reaching almost three times that of any other region. These increases were reflected within the average data despite the peak values being located at two very small areas located over the semi-tendinosus and semi-membranous tendons. With P2 being of a two strap design, it was not subject to these peak pressures, and consequently was ranked by the subjects as having the lowest strap pressure. The significant differences in peak values between P1, P3 and P4 were also identified within the subjective responses.

The middle strap applied a more consistent pressure throughout the running stride compared to the top strap, with no significant differences between conditions in terms of peak or average pressure. P2 was the only condition where the middle strap was identified as a source of discomfort within the subjective results. This could be due to the location and decreased contact area of the strap rather than as a result of differences in pressure.

Finally, no significant differences were found between conditions in terms of peak pressure under the bottom strap, despite P2 having a significantly smaller contact area than the other three pads. P3 had a significantly higher average pressure throughout the running stride, which was reflected in the subjective assessment with four subjects identifying it as a cause of discomfort.

The results suggest that there is a relationship between perceived pad movement and contact area with greater variations in contact area resulting in higher levels of perceived pad movement. With regards to fit, the results suggest that pads with a larger contact area and fewer areas of high pressure are perceived to be of a better fit. Finally, it was found that overall comfort was affected by contact pressure; pads that caused increased peak and average pressures, along with contact area variation, were perceived to be less comfortable. Therefore, to maximise end-users' perceived comfort, contact area under the pad needs to be maximised, reducing areas of high pressure and in turn minimising average pressure. The pad also needs to apply a consistent pressure around the leg to minimise perceived movement of the pad throughout the running motion.

Chapter 7

A product design specification and concept design for a cricket leg guard

This research has been conducted as part of a larger collaborative project between the Sports Technology and Additive Manufacturing (AM) research groups based at Loughborough University. The collaborative project has incorporated six different work packages, focusing on a variety of areas including comfort, material development, design tools, impact absorption and the biomechanics of injury. Through the collaboration of the six work packages a product design specification for a cricket leg guard has been developed. This chapter details the development of the product design specification (PDS) focusing on the elements that this research has contributed to. Working in tandem with the design engineer and impact specialist on the project, a concept design has been developed, based on the PDS. The aim of the concept was to demonstrate how the results of this research could be embodied in a future pad design, to improve comfort, fit and performance. Although the focus was on fit and ergonomic aspects of the concept pad, protection was also considered. Research in this area of the project is still ongoing and, as a result, interim data had to be used.

7.1 Product design specification (PDS)

A PDS is a document based within the design core, consisting of design requirements and end-user needs. This document is the basis for all subsequent stages in the design process, acting as a control mechanism for all design activities (Pugh, 1991). The PDS document itself is seen as a dynamic document, as it can be updated as the design process progresses (Pugh, 1991). The starting point for a PDS is typically market research and testing of existing products, as has been demonstrated within Chapters 2 to 6; this systematic approach enabled a more detailed and comprehensive fundamental control mechanism to be developed.

A PDS typically incorporates thirty-two constituent elements ranging from performance to maintenance and product lifespan. The research within this thesis has concentrated on comfort, therefore, the elements of performance, size, weight and ergonomics will be the primary focus of this chapter. The full document is detailed within Appendix 7.

7.1.1 Performance

The performance element of the PDS incorporates details on protection, contact pressure, and thermal comfort, each of these is discussed in sections 7.1.1.1 to 7.1.1.3.

7.1.1.1 Protection

The online questionnaire on perceived protection (Chapter 3) revealed the regions where cricketers' perceive they need the greatest amount of protection. The results indicate that more protection is required down the central shin and in the centre of the knee, compared to the outside edges of the pad. Less protection is required at the inside edge, top and bottom of the pad. These results were compared to impact results taken from existing pads (Walker, 2009; Webster *et al.,* 2009). Several leg guards were each mounted on a freely suspended anvil (mass = 7.87 kg) and impacted at 16 different locations by a 0.163 kg ball travelling at 31.3 m/s. Six accelerometers measured the acceleration of the pad/anvil system at impact for all six degrees of freedom, from which maximum transmitted force was calculated using Newton's 3rd law. The impact results indicated a similar trend, highlighting that lower peak transmitted forces were experienced within the areas perceived to require greater protection, as demonstrated in Figure 7.1. These results were also compared to the British standard (BS 6183-3:2000) for cricket batting pads. Within BS 6183-3:2000, peak transmitted force is measured using a drop test, where a pad is attached to a steel anvil, which is mounted on to a load cell, then impacted by a steel hemispherical impactor (mass = 2.5 kg) producing an impact energy between 5 J and 40 J, resulting in a maximum impact velocity of 5.66 m/s. For a cricket leg guard to meet the requirements of BS 6183-3:2000, the maximum transmitted force must not exceed those stated in Table 7.1. Using the impact results from Walker's (2009) testing and maximum transmitted forces given in BS 6183-3:2000, a minimum protection level for each zone of the pad was determined (Table 7.1), to ensure that protection levels will be equal to or greater than that provided by existing pads.

Zone	Maximum transmitted force		
	BS 6183-1:200 (5.66m/s impacts) (kN)	Transmitted Force at 31.3 m/s (kN) (Walker, 2009)	PDS Maximum Transmitted Force at 31.2 m/s (kN)
1	6	9.95	8
2	6	6.71	6.5
3	5	6.05	5
4	6	6.71	6.5
5	6	8.17	8
6	5	5.70	5
7	6	8.12	7.5
8	6	9.65	7.5

Table 7. 1: British standard, current pad and target protection levels

7.1.1.2 Contact pressure

Contact area, peak and average pressures were documented for the pad, top strap, middle strap and bottom strap in Chapter 6 for a range of different pads. It was concluded that, to maximise perceived comfort and fit, the contact area needs to be maximised and remain constant during a stride, with reduced peak and average pressures exerted on the leg. Four existing pads were tested with P2 emerging as the best performing pad in terms of perceived comfort, fit and pad movement. Therefore, the PDS specifies that the contact area must be greater than 220 cm^2, with a maximum variation in contact area of 4%, to further reduce perceived pad movement. These values were typically achieved with P2.

The top strap was identified as a major source of discomfort and regions of high pressure were evident in the measured contact pressures behind the strap. The online questionnaire results (Chapter 3) illustrated that, although cricketers found the top strap to be uncomfortable, they did not like pads that have a two strap design, due to the top of the pad not being attached to the leg. Therefore, in accordance with the findings in Chapter 6, the PDS states that no area of the pad must produce a peak contact pressure of 75 kPa or an average pressure of 30 kPa. These values were specified as the contact pressure results for P2, which was identified as the most comfortable pad, maintained contact pressures below these values throughout the entire running stride. Also the results for the bottom strap of P3 suggest that as peak and average pressure values went above this, negative responses were recorded in terms of contact pressure.

7.1.1.3 Thermal

Within the comfort model developed in Chapter 2, 'Thermal comfort' emerged as having an effect on perceived comfort, however, it was considered to be significantly less important than 'Fit', 'Protection' and 'Weight'. Therefore, for the PDS, current pads were benchmarked in terms of dry and wet insulation. The thermal insulation was measured through the use of a thermal manikin (Newton) in a climate chamber (Figure 7.2). The skin temperature was set to 34°C, with an ambient temperature of 20°C whilst measuring dry heat loss, and 34°C for wet heat loss, with a wind speed of 0.1m/s. P1, P2 and P3 (Figure 2.2) were tested, with heat loss for the entire leg and specifically the shin area being measured (Table 7.2). From these results, a maximum dry insulation value of 0.18 m^2°C/W for the whole leg and 0.33 m^2°C/W for the shin area was set to ensure that the new leg guard design equalled or improved on existing pads. In terms of wet insulation, maximum values of 26.4 m^2Pa/W and 106.26 m^2Pa/W for the whole leg and shin area, respectively, were set.

Pad	Whole leg		Shin	
	Dry insulation (m^2°C/W)	Wet insulation (m^2°C/W)	Dry insulation (m^2Pa/W)	Wet insulation (m^2Pa/W)
P1	018	32.4	0.33	151
P2	0.18	26.4	0.55	984
P3	0.19	29.2	0.36	106
PDS	0.18	26.4	0.33	106

Table 7. 2: Thermal manikin results for P1, P2 and P3

7.1.2 Size

The size of a pad, included within the 'Fit' dimension of the comfort model, has a significant effect on perceived comfort. The width and length of the pad were specifically identified, with short pads perceived to provide inadequate protection and long pads restricting motion when playing shots and running. There is a large variation in the length of pads available commercially (Figure 7.3), however, a preference was found in Chapter 6 towards P1 and P3 for pad length and, therefore, within the PDS it is stated that the pad length must fall between 645mm (P1) and 670mm (P3) to satisfy the majority of users.

It has been found that pad width can affect running speed and perceived restriction. From the running analysis described in Chapter 5, it was determined that to minimise interference with the natural running stride, the pad must not add more than 40mm to the inside of each leg. Therefore, it has been specified in the PDS that each pad must not increase leg width by more than 80mm in total, and in particular not add more than 40mm to the inside of the leg.

7.1.3 Weight

Various pads have been tested during this project varying in construction and mass (Table 7.3). There has been a consistent preference for light weight pads; in Chapter 2 for example P1, P2 and P5 were preferred in comparison to P3, P4 and P6. These results were also supported in the subsequent subjective and objective testing, with P1 and P2 significantly out performing P3 and P4 in terms of perceived weight and restriction, as well as, running performance. Therefore, the PDS states that a pad must have a mass of 0.85 kg or less, in accordance with the most popular pads currently on the market. This was supported by the WC results within Chapters 4 and 5 as no significant differences were found between the lightest pad (0.5 kg) and the WC (0.9 kg), suggesting that a pad mass of 0.85 kg or less will not impede running or batting performance.

Pad	Pad mass (kg)
P1	0.85
P2	0.54
P3	0.9
P4	0.89
P5	0.72
P6	1.04

Table 7. 3: Individual pad mass for P1 to P6

7.1.4 *Ergonomics*

To maximise performance, PPE needs to provide minimal restriction, allowing the end-user to perform routine movements without having to change their technique as a result of their equipment. Chapters 4 and 5 measured joint angles whilst performing a variety of shots and running, from these results it was possible to identify the range of angles the leg guard must be able to go through without causing restriction, but still maintaining protection. The results in Chapter 4 identified the sweep as the shot where the leg goes through the largest range of motion, with the knee angle ranging from 165° to 60° across all subjects. In Chapter 5 it was found that knee angles range from 140° at the point of maximum extension to 95° at the point of maximum flexion during the running stride. From these results, it has been specified that a pad must allow 120° of motion, ranging from 170° to 50° without restricting the leg, to ensure that all shots and running can be performed with minimal impedance (Figures 4.8 to 4.10 and Figure 5.20).

7.2 Concept design

The second section of this chapter details the development of a concept design based on the PDS, with a particular focus on maximising the comfort and fit of the leg guard, as this has been the main aim of the work presented within this thesis. Although comfort is the primary focus of this design, protection was considered, and results from other work packages were used to make informed decisions about the level of protection required.

7.2.1 Market research

Prior to developing a concept design, PPE used within other sports and industries were considered. Two items of PPE were found to be particularly relevant for providing knee protection whilst not restricting motion. These two items were motorcycle knee pads and shooting kneeling pads (Figure 7.4). These two examples were of particular interest due to the innovative way they articulate at the knee, without sacrificing protection. Knee articulation was seen as a possible way to address two major issues, discomfort caused by the top strap and pads impeding the hands during shot play. This would allow the top strap to be positioned above the knee so that the thigh protection would be fixed to, and move with the upper leg rather than the pad remaining in a straight position when the leg is flexed. The difficulty with these types of design however, is allowing the knee to bend through the full range required without gaps in protection occurring.

When considering the shape, size and protection elements of PPE it was considered necessary to study items of equipment used to provide protection against similar types of impacts, whilst being used to complete similar movements and tasks. A range of baseball catcher's pads were considered (Figures 7.5), which use a hard outer shell with soft padding underneath. This allows the pad to protect by spreading impact loads over a larger area, whilst maintaining its shape and form by wrapping round the leg, rather than relying on straps to pull the pad around the leg. The use of a hard shell was identified as a possible way to reduce the amount of padding needed to protect the leg, due to it spreading the impact force over a larger area, in a similar way to how canes in traditional pads distributed the force longitudinally down the pad.

7.2.2 Overview of concept design

A concept design was developed from the PDS specifically aiming to maximise fit and perceived comfort. The concept design, illustrated in Figure 7.6, incorporates a combination of impact absorbing foams and a hard shell made from Nylon 12, allowing the leg guard to be formed to the shape of the leg and to spread impact forces over a larger area. The concept leg guard also incorporates an articulating knee to help minimise restriction whilst performing routine movements. Finally an elasticated fabric sleeve is used to fasten the pad to the leg, replacing traditional straps (Figure 7.6). The details of the structure, shape and size of the pad are detailed in sections 7.2.2 to7.2.5.

7.2.3 Structure of the pad

One of the main considerations in the development of the concept design was the structure of the pad, in terms of materials and construction. Within existing pads a variety of materials are used, including cane, different grades of EVA foams and plastics, however, the use of Confor foams, has not been explored. Confor foams were identified as a suitable material to be used within cricket PPE, as the polyurethane foams soften and conform when warmed, which should enhance comfort by minimising pressure peaks on the body, but also have high energy absorption characteristics (Davies and Mills, 1999).

Within the concept design it was envisaged that the use of Confor foam would enable less material to be used whilst maintaining a sufficient protection level, due to the foams high energy absorbing properties. Confor foam comes in four different grades (yellow, pink, blue and green) with varying stiffnesses and energy absorption properties. To determine which grade of Confor foam was most suitable for use within a cricket leg guard and how thick it needed to be, impact data from Walker (2009) was used. Within this set of tests, different grades and thicknesses of Confor foams were compared as well as layered structures containing solid plastic plates embedded between foam layers (Figure 7.7). A combination of green (25.5mm thick) and pink (20mm thick) Confor foam with a 3mm Nylon 12 insert was found to provide greater protection than any existing pad; a mean transmitted force of 4.8 kN was measured when impacted at 31.3 m/s by a 0.163 kg mass (Figure 7.8). The data suggests that this combination of foams and plastic will provide a suitable level of protection for the central shin and knee areas and provide up to double the level of protection required at the inner and outer edges of the pad, therefore, giving scope for the pad thickness at the sides to be reduced from 48.5mm, satisfying the size criteria outlined in the PDS. Impact data from Walker (2009) also found that impacting 15mm of green foam at 31.3 m/s with a 0.163 kg mass would produce a transmitted force of 10.8 kN, providing equal protection to that provided by existing pads at Zones 2,4,5,7 and 8. However, due to this pad being of a closer fit, it was determined that varying the pad thickness from 48.5mm in the centre (25.5mm green, 3mm nylon and 20mm pink) to 23mm at the edge (10mm green, 3mm nylon and 10mm pink) would ensure a suitable level of protection was provided. According to the impact results, these dimensions will provide adequate protection as well as allowing the pad to be significantly thinner, which could help reduce running impedance.

7.2.4 Shape and size of the pad

The shape and size of the pad have been identified as significant contributors to perceived comfort, in terms of their effect on protection, restriction and contact pressure. An advantage with using a solid structure within the design was the ability to shape the pad so that it conforms to the leg, allowing the size and shape to be optimised. To optimise the size and shape of the concept design, 3D body scanning and AM were combined, allowing a pad to be designed around the dimensions of an individual's leg. This process involved a 3D body scan being taken, producing a point cloud of the body (Figure 7.9), which then had a surface fitted to it (Figure 7.10). A hard shell was formed using an offset, which can be equal across the whole design, however, for this concept design a variable offset was used to allow for the varying thicknesses of foam. The CAD (computer aided design) model of this surface can then be used to build the part on a laser sintering machine, allowing for a completely custom pad. This process not only allows for the pad to fit to the leg, increasing contact area, but also allowed the individual to specify the length of the pad, rather than being limited to a set length.

7.2.5 Knee area

The knee area has emerged as a significant factor for leg guard design, in terms of its appearance, protection provided and influence on range of motion. In Chapters 2 and 3, players had a preference for a pad with a defined knee roll, although there was a clear dislike for pads that were wide at the knee, as they were perceived to reduce running performance. Another key consideration for the concept design was the flexibility of the pad at the knee, as pads which did not bend with the knee were disliked because they could get in the way of the hands whilst playing shots.

Current pads on the market tend to adopt one of two designs for the knee area (Figure 2.2) - a segmented knee roll separated into multiple segments (typically 3) or no clearly defined knee area (for example P2). Although both these design have been used across a wide range of pads, they both provide very limited flexibility as a result of the stiff materials used, resulting in the pad remaining straight when the knee is flexed. This has several disadvantages including restricting shot ROM, gaps opening between the pad and leg above the knee, high strap pressures and reducing contact area whenever the leg is bent. The inclusion of an articulated knee, as used within motorbike knee protection, was considered advantageous, as this would allow the top of the leg guard to remain in contact with the thigh at all times, increasing contact area, whilst minimising restriction.

Within the concept design, the knee was made to articulate through the use of a hinge along the line of the knee joint centre, with the top section (thigh protector) being encapsulated by the bottom half of the pad (Figure 7.11); this allowed the knee to be bend through the 120° needed, without the leg being exposed to the ball. Through the use of this design, additional protection would be provided to the centre of the knee, which covers the patella, whilst minimising pad size at the inside and outside of the pad.

7.2.6 Strap design

The concept pad illustrated in Figure 7.6 can be customised to an individual resulting in a pad which is contoured to the leg and can articulate at the knee. The advantage of these two factors is that the straps are there to stop the leg guard detaching whilst moving, rather than to pull the pad against the leg, so that it bends around the shape of the body. Material selection is of key importance, as the wrong material could result in the leg becoming extremely hot, and restrict the natural expansion/contraction of the muscle. Therefore, it was decided that the use of a breathable, high wicking material (as used in compression garments) would be appropriate, aiding moisture transportation away from the skin and increasing heat dissipation through evaporation. The concept leg guard is attached to the leg through the use of two Nylon/Polyester (as used in compression garments) sleeves, as depicted in Figure 7.6. The use of sleeves rather than straps will result in strap contact area being significantly larger, allowing average contact pressure to be reduced.

7.2.7 Summary of concept design

The concept design was developed based on several criteria outlined within the PDS (Appendix 7). The focus of this design was on factors affecting perceived comfort, with particular emphasis on fit, protection and weight. Table 7.4 compares the PDS with concept design data taken from the CAD model (Figure 7.11) (developed by the design engineer). Thermal comfort, running performance, average pressure and peak pressure of the concept design are not discussed within this section, as these features require physical testing and can not be estimated from the CAD model. From the comparison of the PDS and concept design (Table 7.4) it is apparent that the concept design satisfies the PDS in terms of mass, predicted protection, inside leg thickness, contact area and pad length.

7.2.8 Conclusion

The test data provided within Chapters 2 to 6 enabled a PDS to be developed specifying size, weight and levels of protection. The PDS was used to develop a concept design where the main focus was perceived comfort and protection, with the aim of maximising player performance and end-user satisfaction. Through the use of new technologies such as 3D body scanning and AM, a concept design was developed which is customised to the individual. The concept design was developed from a 3D body scan, resulting in the pad fitting to the individual's leg, maximising contact area. The inclusion of Confor foams and a Nylon 12 shell enabled the thickness of the pad to be minimised, whilst maintaining adequate protection. Finally, an articulating knee was incorporated within the design, to prevent the pad from affecting the player's batting technique. The articulating knee and conformity of the design also allowed for the strap behind the knee to be removed, which was a major source of discomfort. The concept design demonstrates how the results of the testing and the knowledge gained throughout the project can be embodied in a design that should be more comfortable to wear and impact running performance to a lesser extent, compared to existing pads.

Criteria	PDS		Concept design
Mass	<0.85kg		AM insert =0.343kg Outer foam =0.200kg Inner foam = 0.285kg Total = 0.828kg
Length	645-670cm		Built to subject's specification
Inside leg thickness	<40mm		26mm
Protection (transmitted force at 31.2m/s)			
• Minimum transmitted force	5kN		4.8kN (predicted from impact testing on 100x100mm samples)
• Maximum transmitted force	8kN		8kN (predicted from impact testing on 100mm x 100mm samples)
Thermal	Dry	Wet	
• Shin	≤0.33m^2°C/W	≤106.26 m^{2}Pa/W	
• Leg	≤0.18m^2°C/W	≤26.43 m^{2}Pa/W	
Knee range of motion	120°		120°
Contact area	>220cm^2		Up to 1212cm^2

Table 7. 4: Comparison between concept design and PDS

Chapter 8

Conclusions and Future Work

8.1 Conclusions

This research represents a first investigation into the perceived comfort and fit of personal protective equipment in sport, and has developed an understanding of factors affecting perceived comfort. A new hierarchical model has been developed allowing the most influential features affecting perceived comfort to be identified and objective tests developed to help maximise end-user satisfaction.

Two comfort models have been developed for cricket leg guards and taekwondo hogus which contain the same six dimensions of comfort. These items of PPE were selected as they are used within very different sports, varying in intensity, duration, environment and type of impacts that they protect against. The results identified only subtle differences in terminology were identified between the two models, down to the lower order sub-themes, where, more specific design features started to be identified. The two models also demonstrated a high degree of similarity in terms of inter dimension links, as demonstrated by the relationship models. Differences between the models did occur when considering the relative importance of each dimension, suggesting that individual comfort models for each piece of equipment are necessary. Although there were distinct differences in perceived importance with regards to 'Protection', 'Weight' and 'Thermal comfort', the majority of players for both sports perceived 'Fit' as the most important factor affecting comfort.

Within the cricket leg guard comfort model, several contributing factors were identified within the 'Fit' dimension, including, awareness, customisation, flexibility, shape to the body, size, movement and strap design. Player movement, in terms of shot range of motion and performance, was focused on. To assess these, a method was developed to allow 3D motion to be assessed whilst players wore leg guards that covered the anatomical land marks typically used to track motion. This method involved the use of cluster markers on the thigh and foot, allowing joint centres of the knee and ankle to be calculated, despite there being no markers at either location during dynamic trials. The use of cluster markers allowed an accurate model to be developed which could determine lower extremity joint angles. Joint angle data was combined with shot impact data and a subjective assessment of three pads, as well as for a no pad and weighted comparison whilst performing three different shots. The shot impact data suggested none of the pads or the weighted comparison significantly affected the performance of any of the three shots when compared to batting without pads, however, the subjective results suggested P3 was perceived by the majority of players to significantly restrict motion when compared to P1 and P2. These results were compared to joint angle data but there was no consistent trend in terms of actual restriction, suggesting that the perceived restriction was caused by other factors such as contact pressure, weight and size of the pad.

A running speed study was conducted in two parts, initially focusing on the effect of cricket leg guards on running and turning speed, whilst the second part aimed to investigate possible causes of running impediment. The running time study identified that running in pads did significantly affect running performance, as did the weighted comparison; however, the level of impediment was dependent on type of pad worn. The results suggest that the loss of performance was due to a decrease in straight line running speed, as opposed to time taken to turn. The decrease in running speed could not be solely attributable to additional weight, as the weighted comparison was of equal weight to the heaviest pad (P3), yet running times were significantly slower for P3. These findings were further investigated through the use of 3D motion analysis and ground reaction force. No significant differences were found in joint angle kinematics at the knee or ankle between the five conditions, although, P3 was found to significantly increase stride width and decrease stride length. These changes in stride parameters were as a result of P3 adding over 5cm to the inside of each leg inhibiting the natural running stride, forcing the cricketer to run with a wider stride, whereas P1 and P2 added less than 5cm so meant the cricketers could maintain a more natural gait, as measured in the no pad condition. Ground reaction force data identified that as a result of changes in running gait, braking forces were increased and propulsive impulse decreased in all padded conditions and the weighted comparison. Changes in anteroposterior forces coincided with increased mediolateral forces for the three padded conditions, suggesting less force was being applied in the direction of locomotion, ultimately decreasing running speed.

Alongside the running data, pad movement relative to the leg was also measured to determine if there was a relationship between perceived and actual pad movement. The pad movement data was compared to subjective data assessing pad movement. Although there were no significant differences between the three padded conditions in terms of rotation about the leg, P3 was perceived to move significantly more than the other pads when running. These results suggest that other contributory factors must have created this perception of the pad moving on the leg whilst running.

From the subjective responses collected throughout the testing it became evident that a key factor in determining perceived fit, with particular reference to pad movement and perceived restriction was the pressure the pad exerts on the leg. Contact pressure was measured for four pads, through the use of an X-sensor pressure mat, whilst running on a treadmill. The contact pressure data was assessed in terms of peak pressure, average pressure and contact area under different regions of the pad - the top, middle and bottom straps and the padded area. Subjective responses correlated with contact pressure data. The top strap was identified as the area applying the highest pressures to the leg and this was also found in the measured pressure data. A link between contact area variation, in terms of position and size, and perceived pad movement was also identified. Pads which had an inconsistent contact area were perceived to move about the leg more. These results suggest that contact area between the pad and leg needs to be maximised, with minimal variation whilst running.

Finally the data collected throughout the testing stages of this thesis was incorporated into a product design specification, with specific sizes, contact areas, contact pressures, protection levels and weights being defined. From this product design specification, a concept design was developed, which utilised 3D body scanning, additive manufacturing and Confor foams as a means of producing a custom made leg guard. The concept design illustrates how data collected through the use of various objective and subjective studies can be utilised to develop new products around the needs of the end-user. This research highlights the successful integration of the end-user within the design process, which in turn could lead to increased user satisfaction and perceived comfort.

8.2 Future work

This project has developed an approach to incorporate the end-user into the design process through the use of subjective and objective measurements. A comfort model has been developed for both cricket and taekwondo but only the dimension of 'Fit' has been investigated in depth and only for cricket. The testing of the other general dimensions through the use of player testing is one avenue of future work, as is the development and testing of a prototype leg guard, both of which will be discussed within this section.

Within the PDS, protection levels were discussed with existing products being benchmarked. Further investigation needs to be conducted in order to fully understand the mechanisms of injury, as it is not known if current pads provide enough or even too much protection, which could have significant affects on the size and weight of the PPE.

The research has presented data on running performance identifying a maximum weight for the concept design; however, further analysis is needed regarding the affect of weight on energy consumption and movement speed. The use of inverse dynamics could be used to determine the difference in moment size when different masses are added to the leg, whilst running at a set speed. This data would allow an understanding to be gained regarding the effect of cricket leg guards on movement efficiency, helping a leg guard to be developed that will minimise fatigue whilst batting.

Thermal comfort was another factor players' perceived to affect comfort, therefore further player testing is required to assess the significance of differences in levels of insulation provided by leg guards. Work by Roberts (2008) illustrated that using lab based exercise protocols that replicate game conditions by inducing a heart rate pattern similar to that experienced in a match allows a more accurate analysis of skin and core temperature to be conducted, whilst allowing subjective feedback to be collected throughout the testing. This method could be employed to assess thermal comfort of cricket leg guards throughout an innings, to determine if there is a correlation between skin temperature and perceived comfort, as well as determining how sensitive players are to different levels of heat restriction.

The inclusion of data from the testing outlined within this section will allow a more complete PDS to be developed, which can then be used to further develop the concept design. Once the design has been adjusted to incorporate this new data, prototype leg guards could be manufactured and tested, determining if they satisfy the requirements outlined within the PDS. Once these tests have been conducted further subjective analysis needs to be conducted for the design to be optimised.

Finally the approach outlined within this research could be replicated with other pieces of sporting equipment, including further analysis of the taekwondo hogu.

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Figures

Figure 1. 1: Pontrelli's "Comfort's Gestalt" (1977)

Figure 1. 2: Sontag's "Human Ecological Approach" (1986)

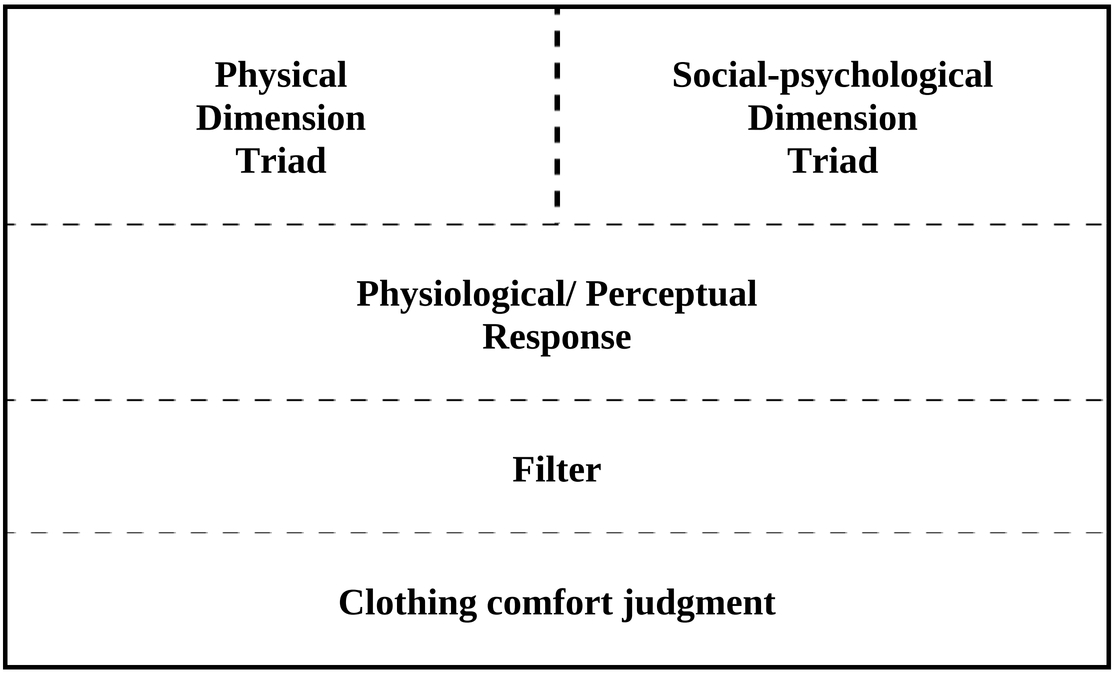


Figure 1. 3: Branson and Sweeney's comfort model (1991)

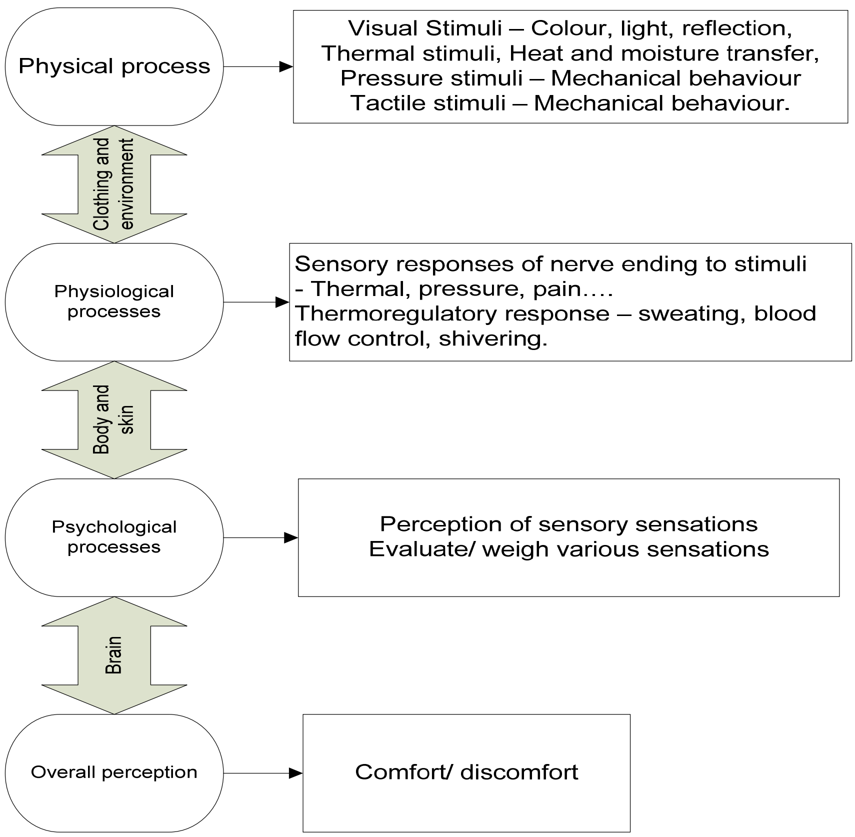


Figure 1. 4: Subjective perception of comfort (Li, 2001)

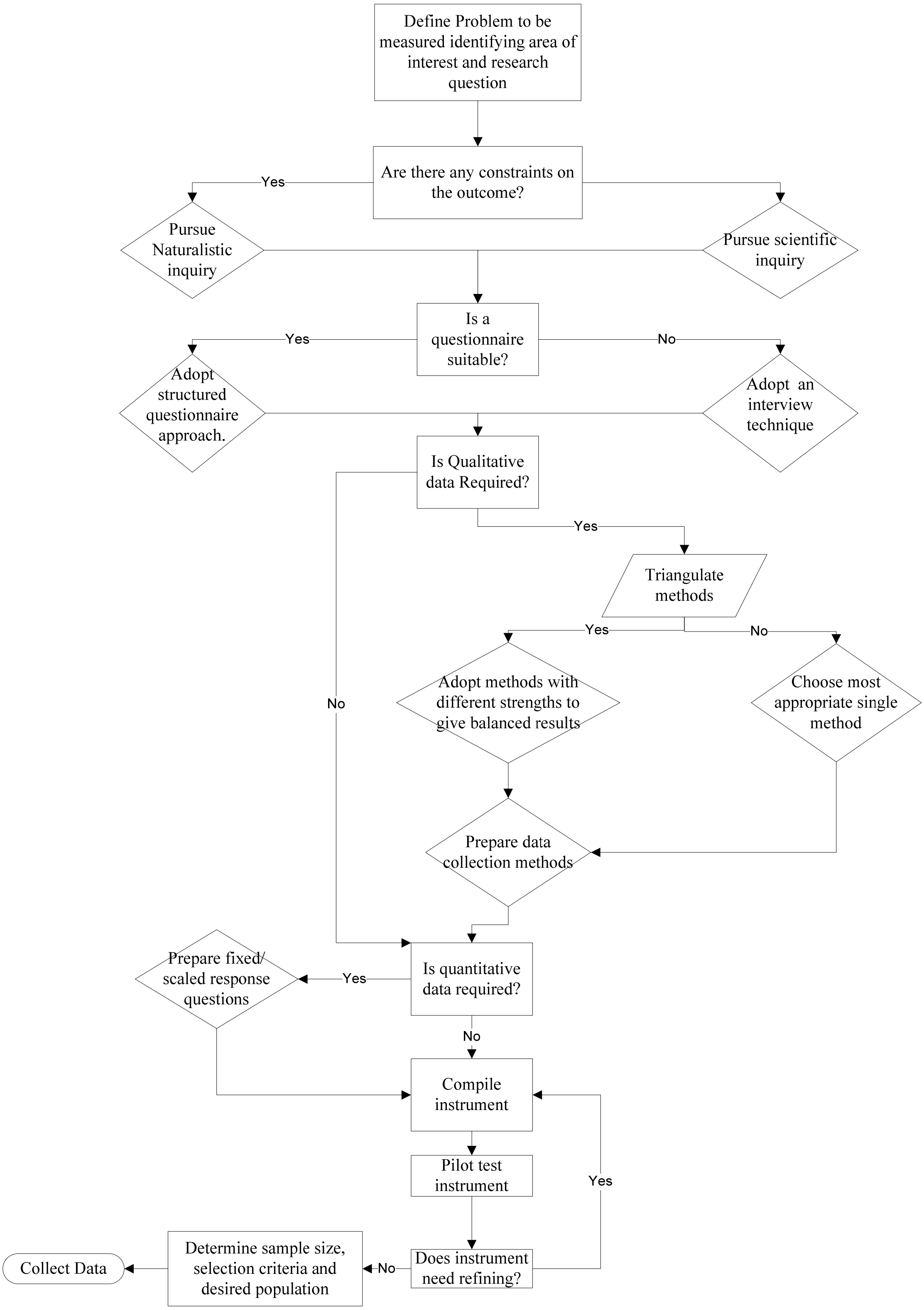


Figure 2. 1: Modified version of Roberts (2001) study design process

Figure 2. 2: Range of cricket leg guards used within testing

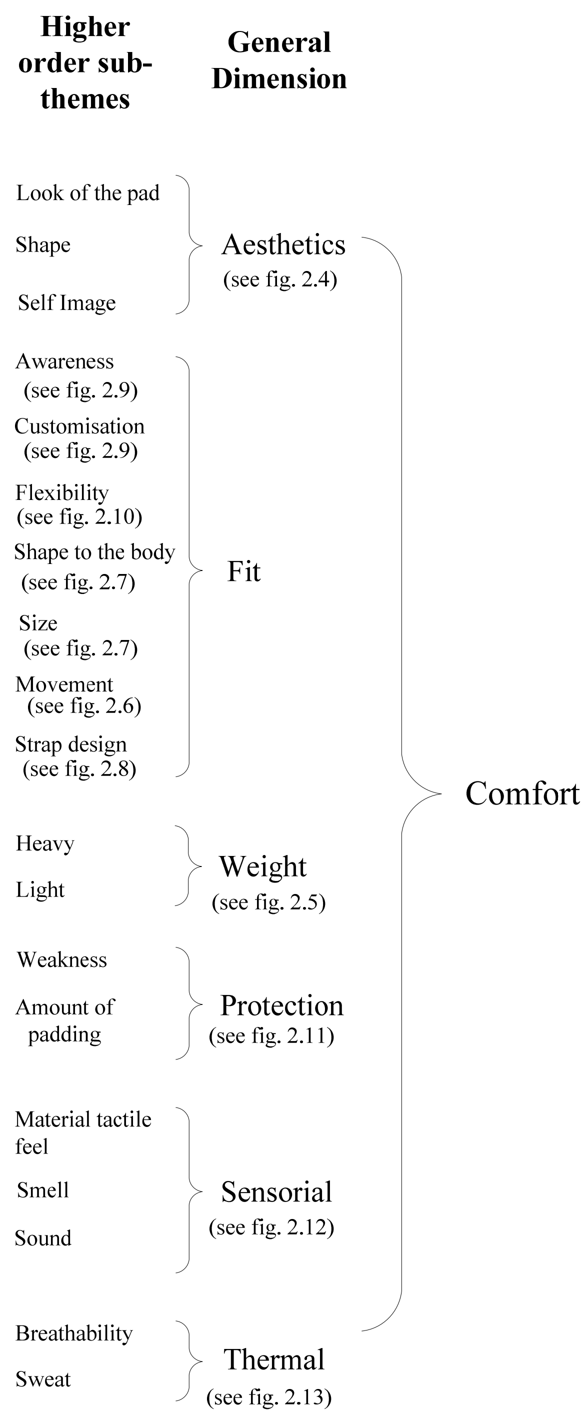


Figure 2. 3: General dimensions and higher order sub-themes for cricket

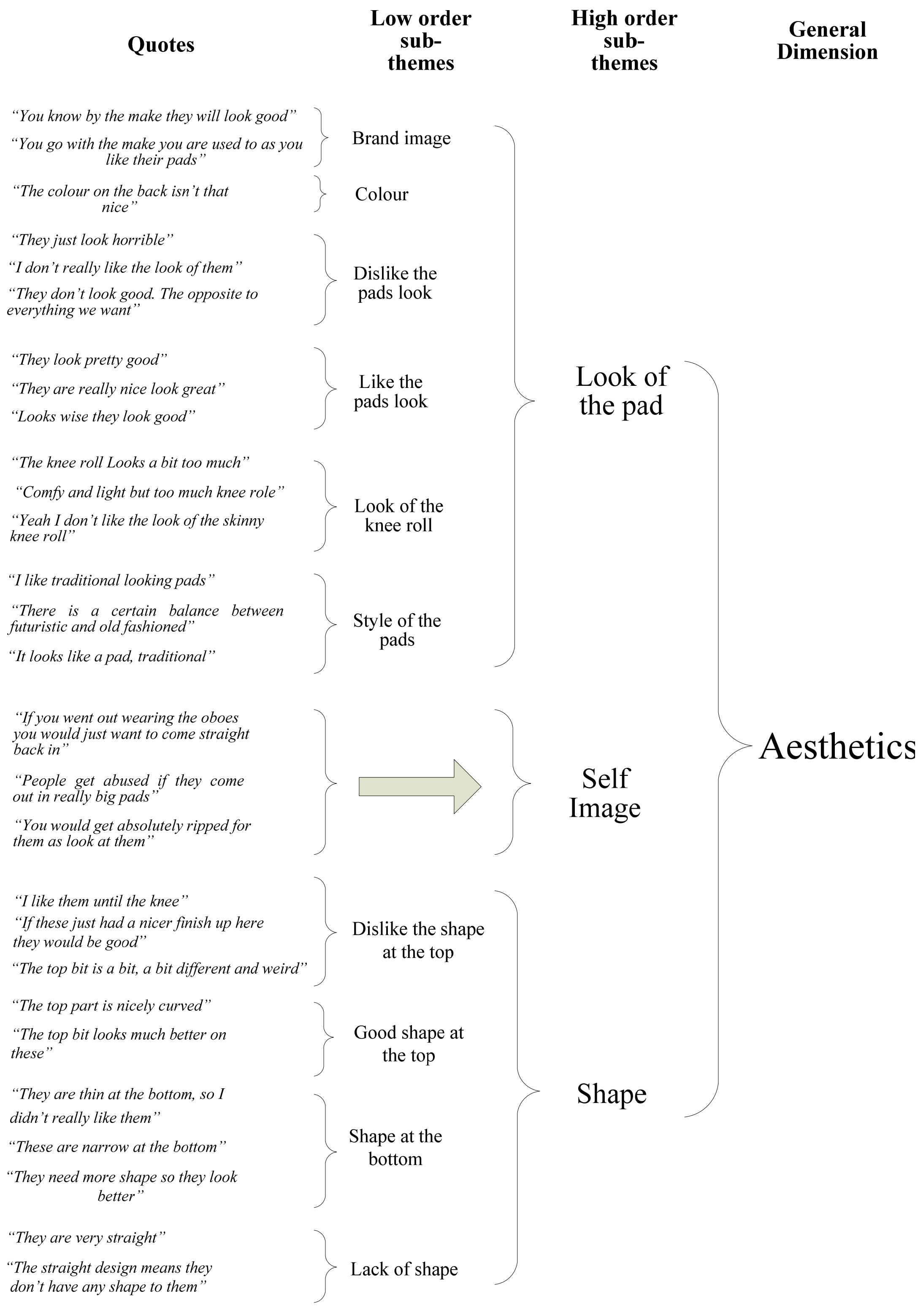


Figure 2. 4: General Dimension of Aesthetics for cricket

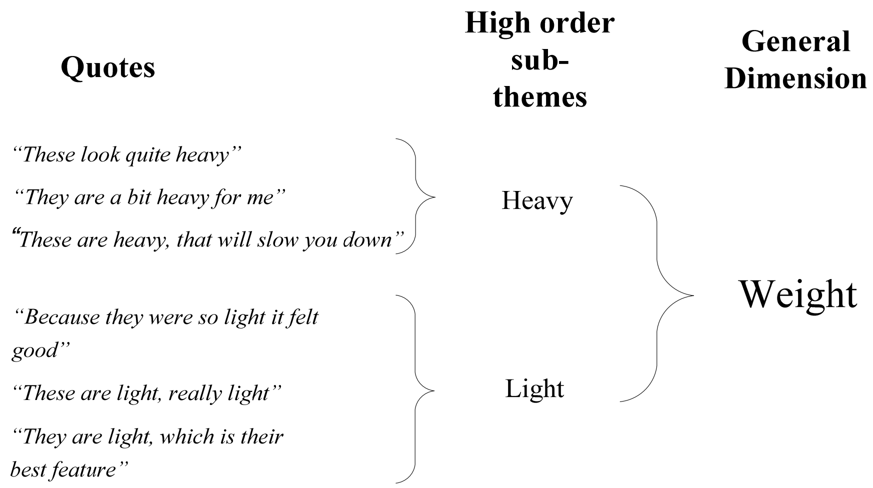


Figure 2. 5: General Dimension of 'Weight' for cricket

Quotes	Low order sub-themes	High order sub-themes
"They just kind of stick out and when your running flap" *"Couldn't run that much in them, they were just awkward"* *"They can be too bulky and difficult to run in"*	Difficult to run in	Movement
"You can run quite nicely in them" *"Canterbury pads were good to run in"* *"They are a good pad easy to run"*	Easy to run in	
"These just stick up they get in the way there" *"The top part of the knee blocks your hands because it pokes out at you"* *"The oboe ones really effected me in my stance"*	Effect technique	
"They aren't easy to move in" *"They were a bit over padded stopping you being able to move properly"* *"When they restrict you they can affect your movement and performance"*	Mobility	
"When they are restricting you can't move to play a shot" *"Any restriction can be bad on performance"* *"Too much padding on these restricted my movement"*	Restricting	

Figure 2. 6: Higher order sub-theme of 'Fit' for cricket – Movement

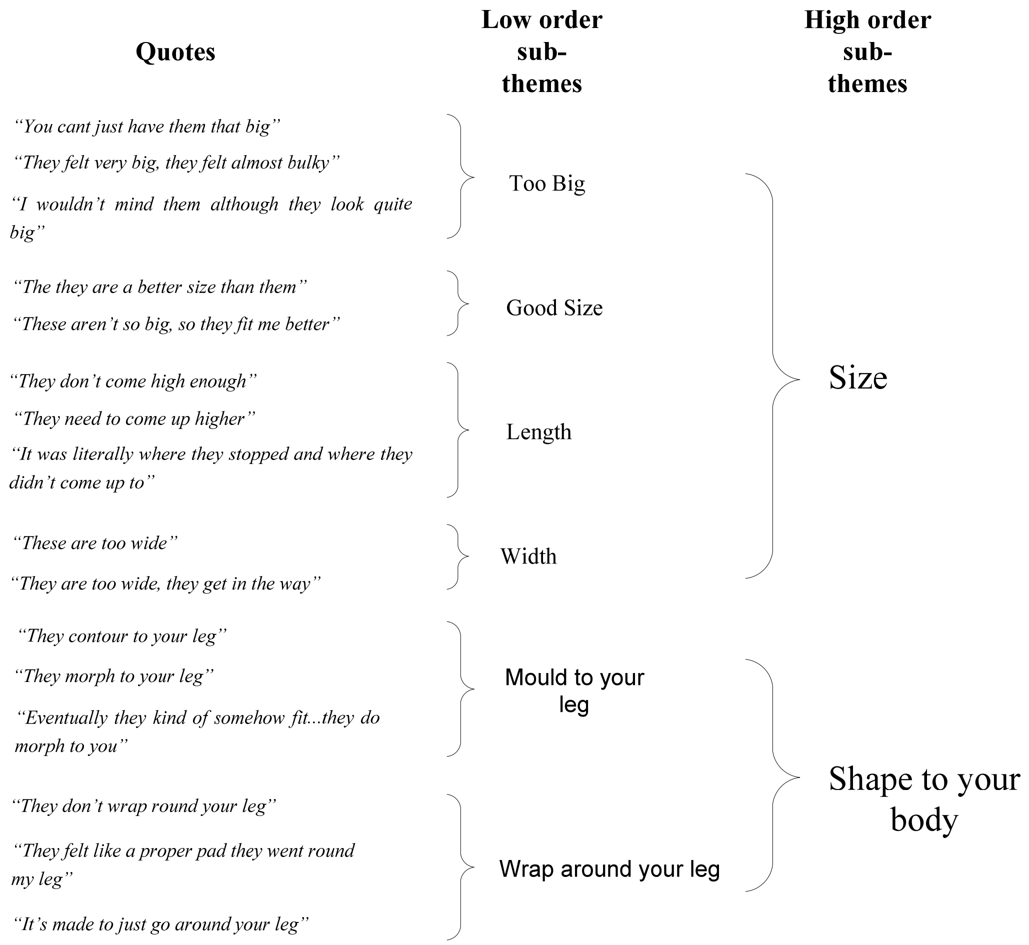


Figure 2. 7: Higher order sub-themes of 'Fit' for cricket – Size and Shape to the body

Quotes	Low order sub-themes	High order sub-themes
"They need to fit all players" *"Different players want to strap pads in there own way"*	Adjustibility of straps	Strap Design
"Some do have 2 straps now, they can be better" *"They were a little bit uncomfortable, with only 2 straps"* *" They only have 2 straps ... so they don't bend at the knee"*	Number of straps	
"They have an extra bit [padding] which stops it rubbing as much" *"The strap didn't cut in, you couldn't really feel them against your leg...the padding was nice"*	Padded straps	
"The strap at the back of the knee becomes uncomfortable and cuts in" *"I felt the straps would cut in"* *"The Narrower straps really dig in"*	Straps dig in	
"New Velcro straps are better" *"Velcro is better than the old buckles"*	Strap fastening type	
"When the straps are to long and stick out is annoying" *"I don't know why they make the straps so long"*	Strap length	
"I prefer the wider straps" *"The width of the straps make a big difference"*	Strap width	

Figure 2. 8: Higher order sub-theme of 'Fit' – Strap Design for cricket

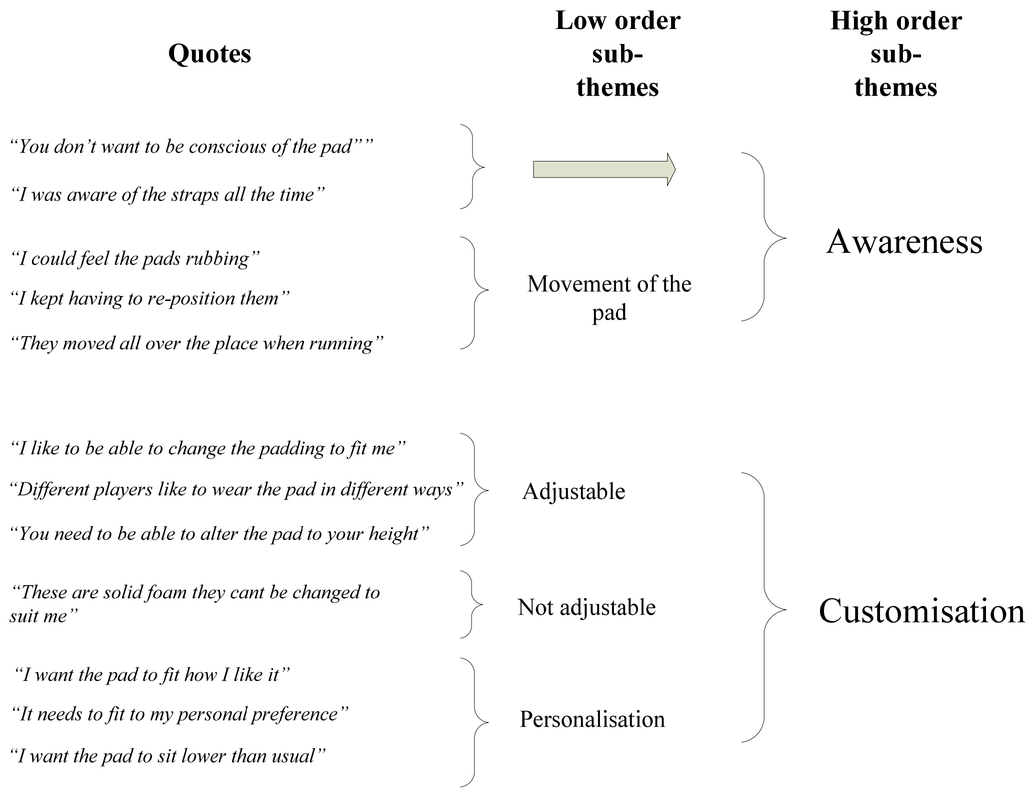


Figure 2. 9: Higher order sub-themes of 'Fit' for cricket – Awareness and Customisation

Quotes	**Low order sub-themes**	**High order sub-themes**
"My only issue with those is they are absolutely rigid" *"Look at this the cane on that its stiff it doesn't bend"* *"They feel quite stiff on your leg when your wearing them"*	Feel stiff	Flexibility
"The best ones I find are like them as they bend back on your knee" *"But they have one fault as they don't bend at the knee"* *"But without bend At the knee what should be covered isn't"*	Flexible at the knee	
"No flex in these" *"One thing I have always gone for is flexibility"* *"I like these, they are flexible"*	Flexible material	
"Not got a lot of bend at the knee to them" *"There is no bend at the knee making them uncomfortable"* *"Well my ones have got a bit of give back, where as these don't as there is no flex at the knee"*	Lack of flex at the knee	

Figure 2. 10: Higher order sub-themes of 'Fit' for cricket – Flexibility

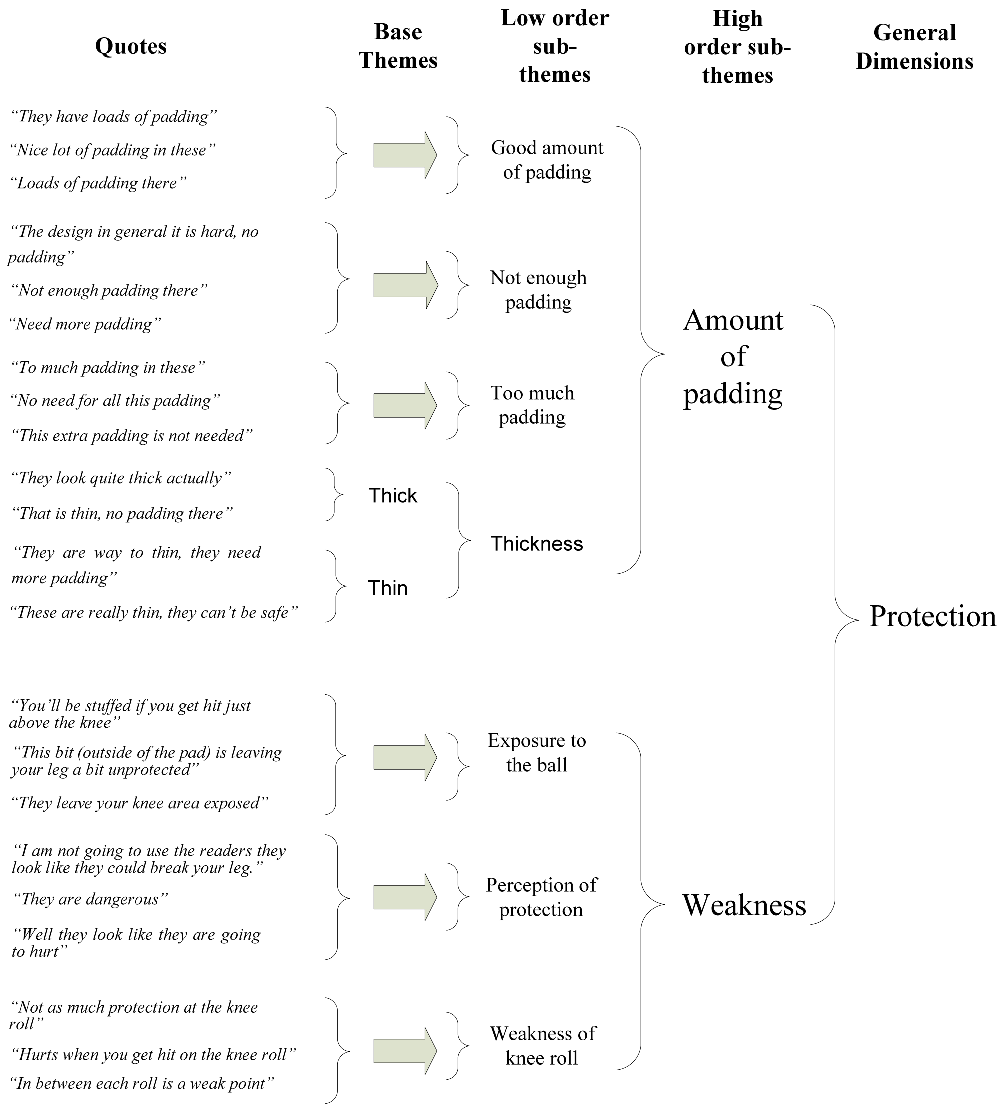


Figure 2. 11: General dimension 'Protection' for cricket

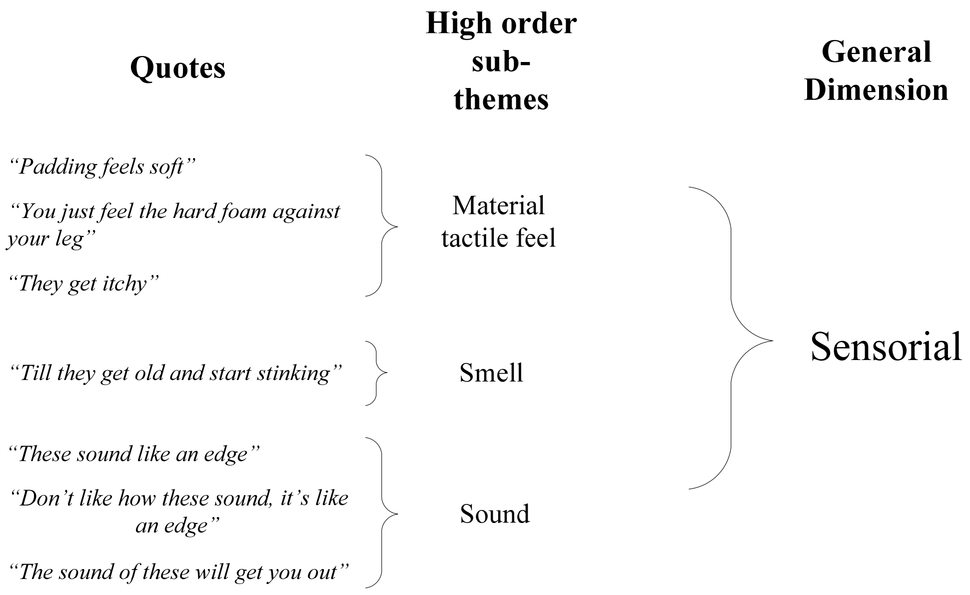


Figure 2. 12: General dimension 'Sensorial' for cricket

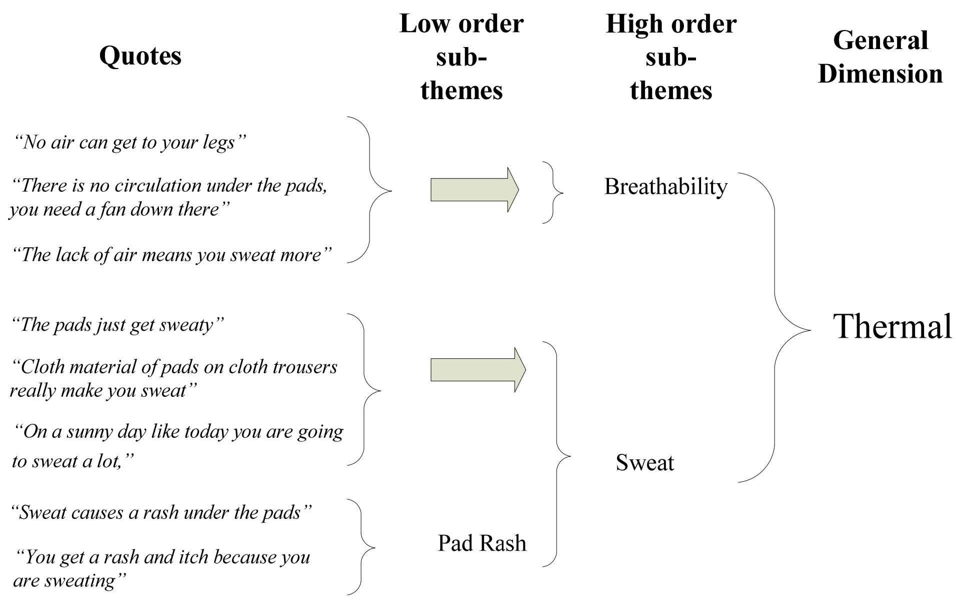


Figure 2. 13: General dimension 'Thermal' for cricket

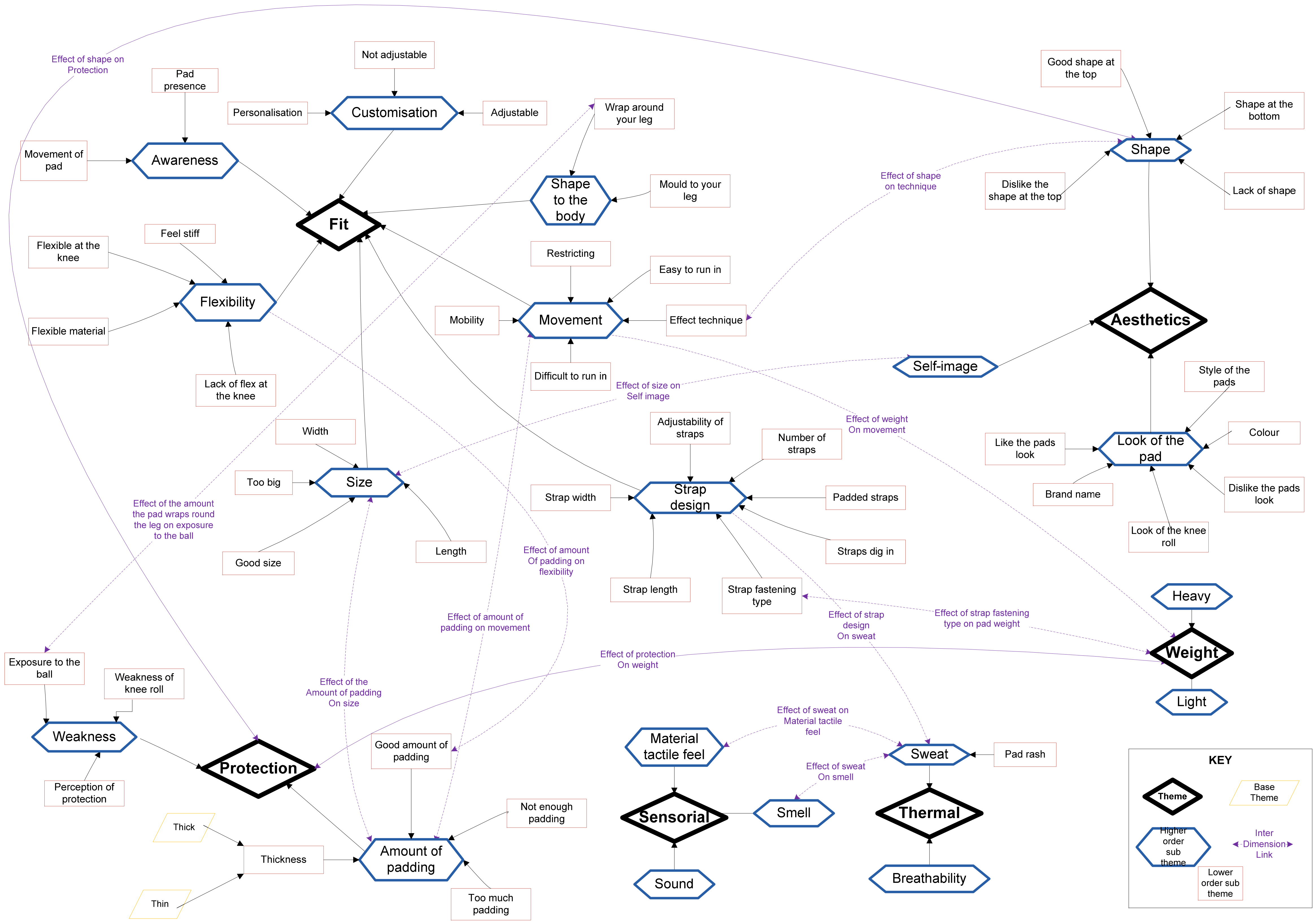


Figure 2. 14: Structured Relationship model for comfort of a cricket leg guard

Figure 2. 15: Taekwondo chest guards

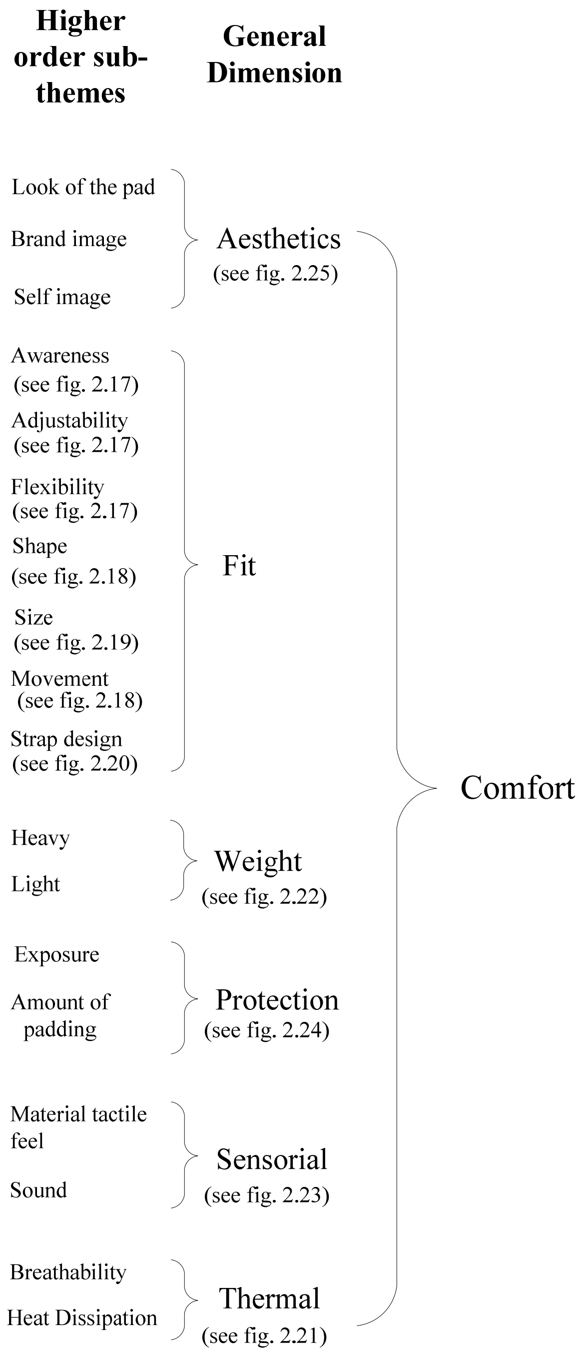


Figure 2. 16: General dimensions and higher order sub-themes for taekwondo

Quotes	**Low order sub-themes**	**High order sub-themes**
"You don't know you really have it on" *"In your head you are constantly thinking about it"*		Awareness
"It stays in place, that's what you need, You wouldn't really want it to move around" *"I think I prefer this pad, as that one seems to move up more so its by your neck, so you are always having to pull it down"*	Movement of the pad	Awareness
"It fits more there (waist) than it does there (chest), so you have got a gap between me and the pad" *"The big gaps aren't affecting me much but they aren't comfortable"* *"It still doesn't feel nice here (Gap at the top)"*	Contact between pad and person	Awareness
"It's not got the elastic so I can't move it around if I want to" *"I don't like the way it doesn't move if you wanted to pull it down"* *"You want to move it to the correct place, whereas this one annoys me as this wIll not move to where I want it to"*		Adjustability
"I think pads could be less stiff" *"This pad is way too stiff"* *"I just don't like the stiffness of it"*	Stiff/ rigid	Flexibility
"I don't like the fact its got no elastic at the top, so there is no give" *"This one gives a little, whereas that one is just dead hard"*	Give	Flexibility
"[I like] it to be a bit more durable and flexible." *"Feels a lot more flexible than the one I usually use"*	Flexible material	Flexibility

Figure 2. 17: Higher order sub-themes of 'Fit' for taekwondo – Awareness, Adjustability and Flexibility

Quotes	Low order sub-themes	High order sub-themes
"Seems to fit to my body more, shape to it" *"It goes round the body more"* *"I think it moulds to your body a bit more"*	Shape to the body	Shape
"You see how that is really long at the bottom, that would be really annoying" *"I don't like this to come down too low either (front flap)"* *"My usual pad doEs not usually have long bits here [front flap]"*	Shape at the bottom	Shape
"Enough clearance to kick, it just feels like nothing is restricting me" *"It's pretty much the same as the other ones nice and free [movement]"* *"I can get my knee up higher to kick"*	Easy to move	Movement
"You see how that is really long at the bottom, that would be really annoying, you wouldn't be able to kick" *"The bottom can start to get in your way of your hips"* *"If it comes down too low it will stop my kicks coming up"*	Prevents movement	Movement
"You feel like they restrict you a little bit" *"They are really thick, and I would just feel restricted in that"* *"There isn't as much freedom in this"*	Restricting	Movement

Figure 2. 18: Higher order sub-themes of 'Fit' for taekwondo – Shape and Movement

Quotes	Low order sub-themes	High order sub-themes
"I think they are a better fit for me, as it's a bit bigger than the others" *"The 3 in this is a little bit bigger than the 3 in the 2nd one. So it fits me better"*	Good Size	Size
"It's too bulky," *"It's just too big, it's dead bulky"* *"I think this one is too bulky"*	Bulky	
"Some pads tend to rub and scratch on your neck, they could do with being a bit wider" *"You need a bit of room around the neck"* *"[it's got] a little bit more looseness around the collar, which is good"*	Collar size	
"This one is really a tight fit, it's really tight around you" *"Seems a bit tighter than the other one"* *"[It's] tighter than the other pads"*	Tight	
"This one kept on coming loose and didn't feel to secure" *"I prefer it a bit lose, just because that's what I am used to"*	Loose	
"That's too thick" *"I think this one is really thick"* *"I don't want them to thick, as you feel like they restrict you a little bit"*	Thickness	

Figure 2. 19: Higher order sub-theme of 'Fit' for taekwondo – Size

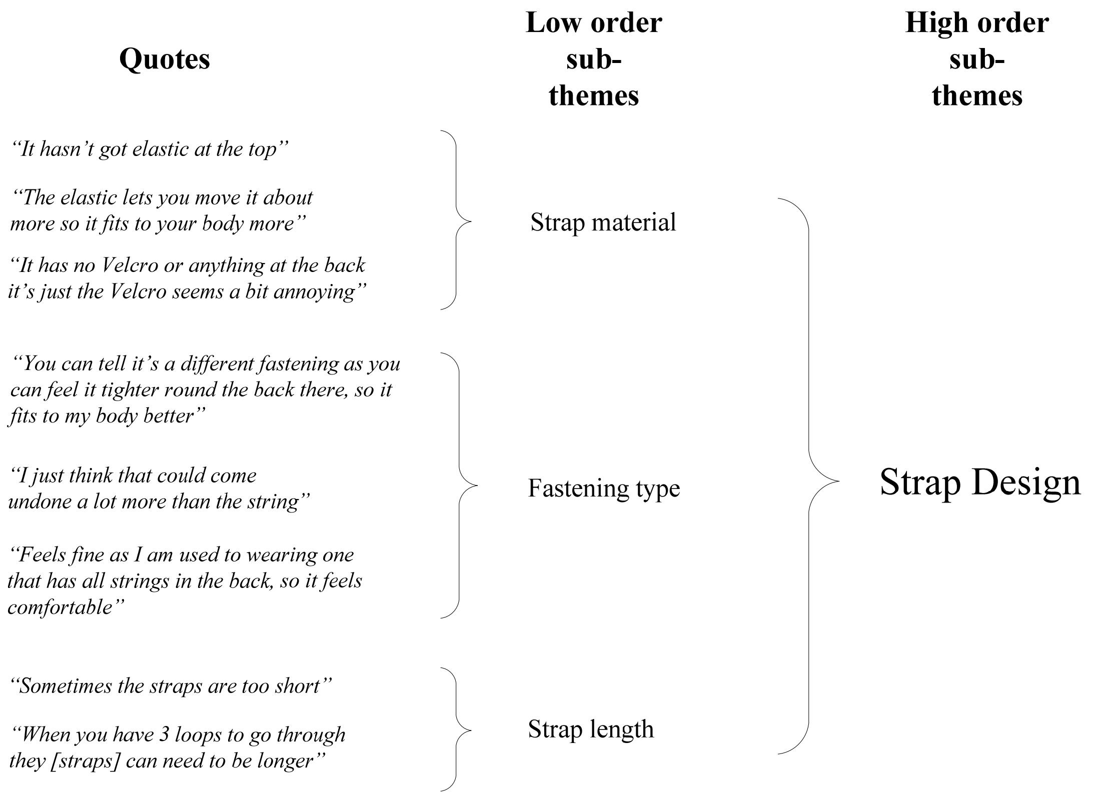


Figure 2. 20: Higher order sub-theme of 'Fit' for taekwondo – Strap design

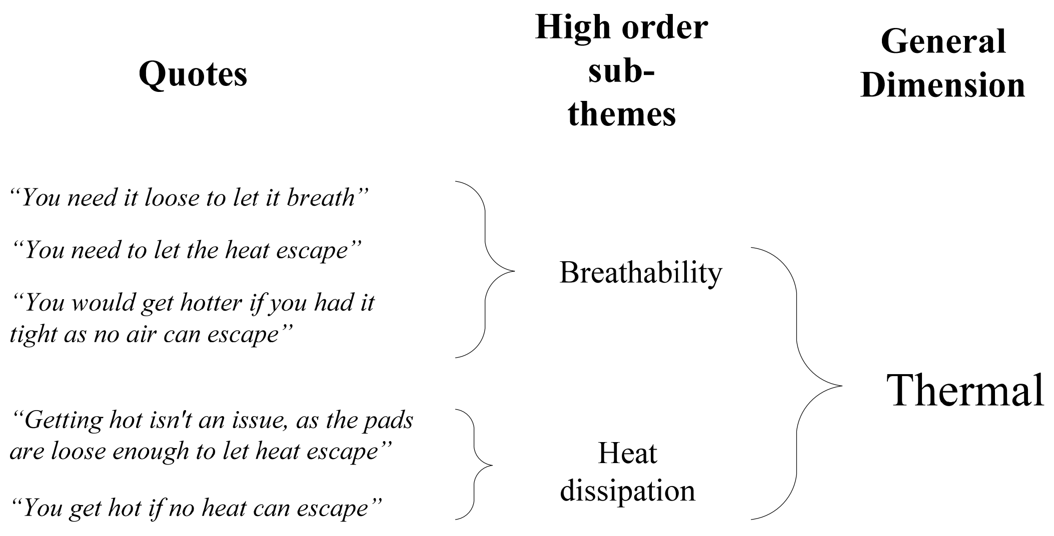


Figure 2. 21: General Dimension of 'Thermal' for taekwondo

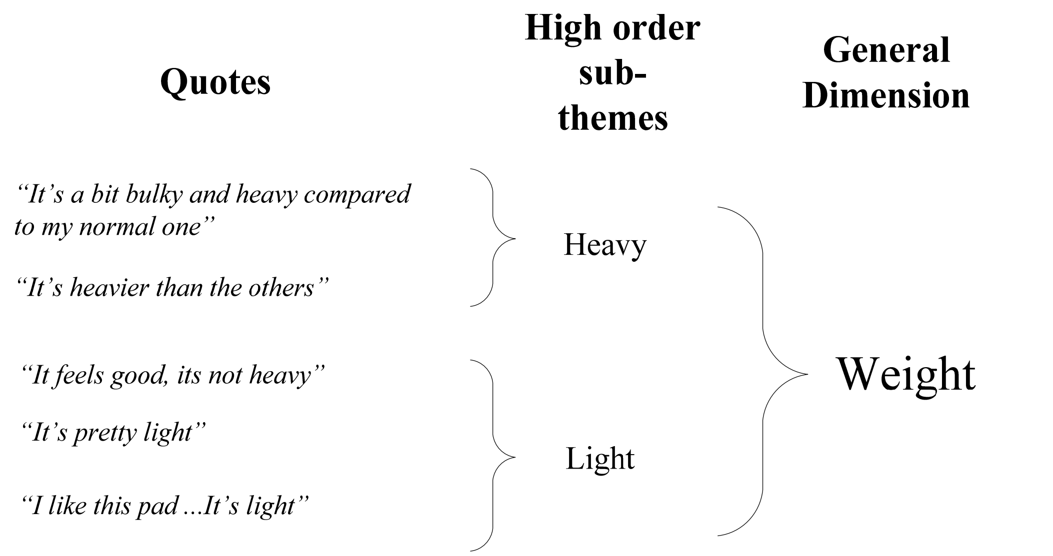


Figure 2. 22: General Dimension of 'Weight' for taekwondo

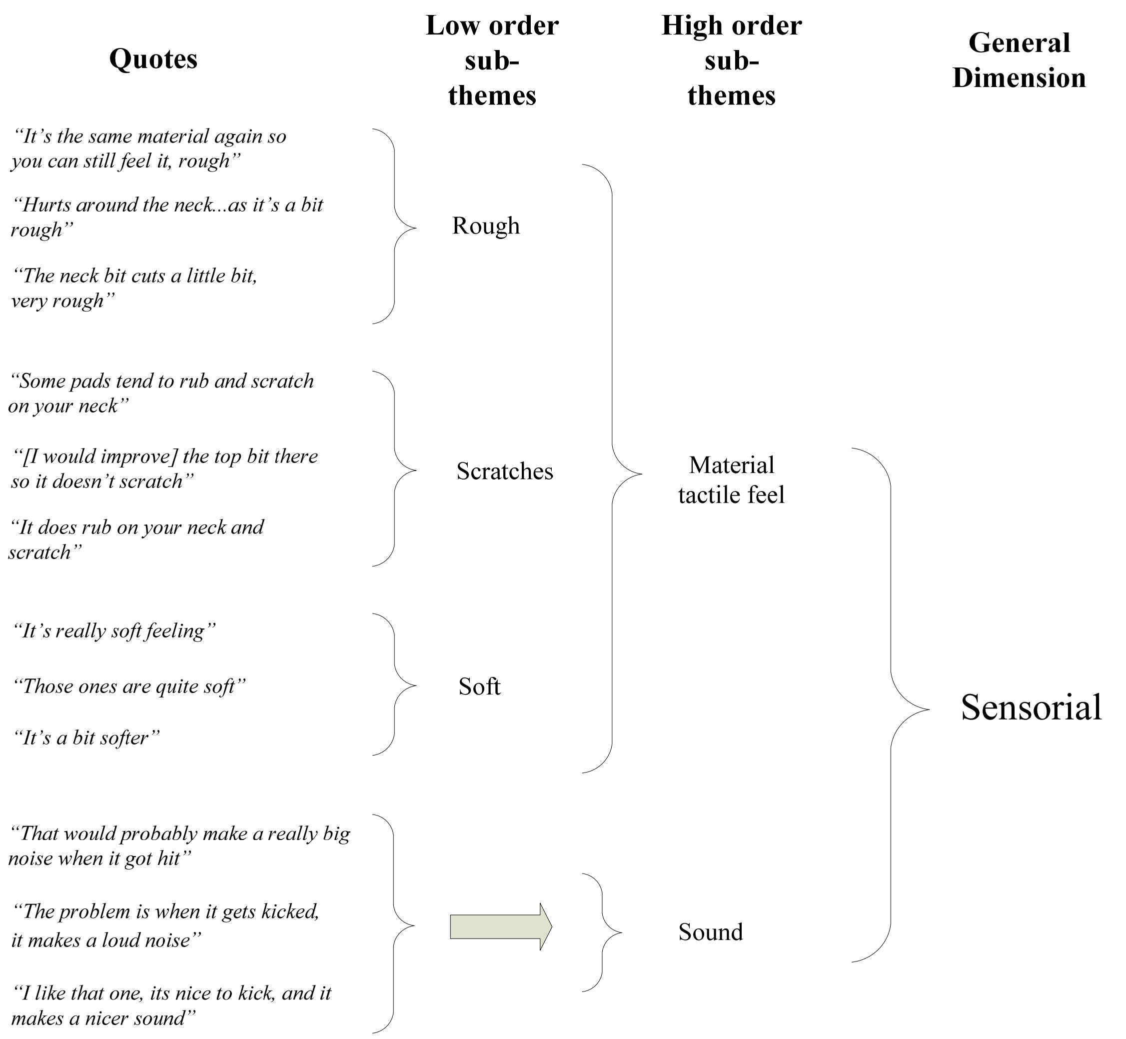


Figure 2. 23: General Dimension of 'Sensorial' for taekwondo

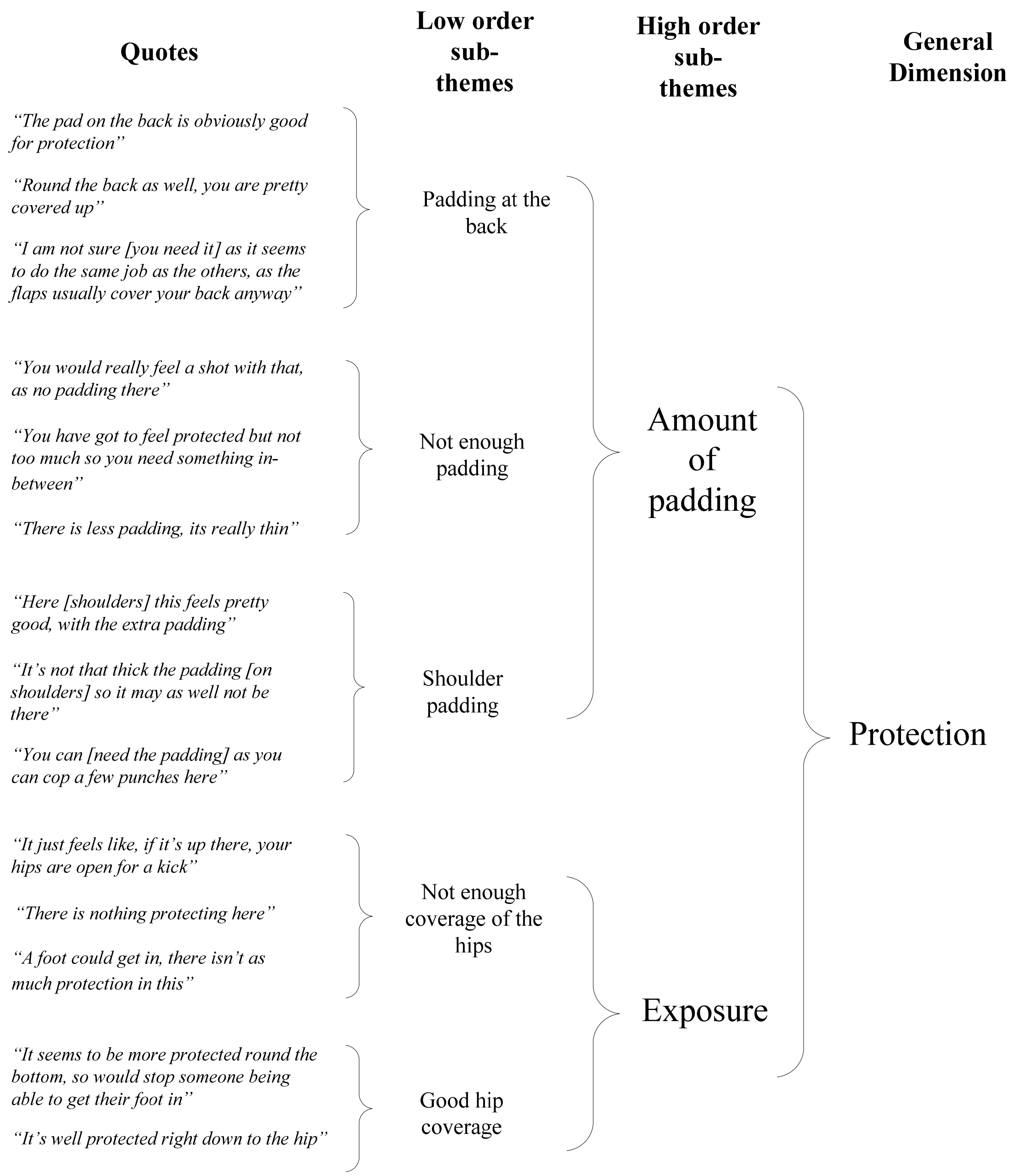


Figure 2. 24: General Dimension of 'Protection' for taekwondo

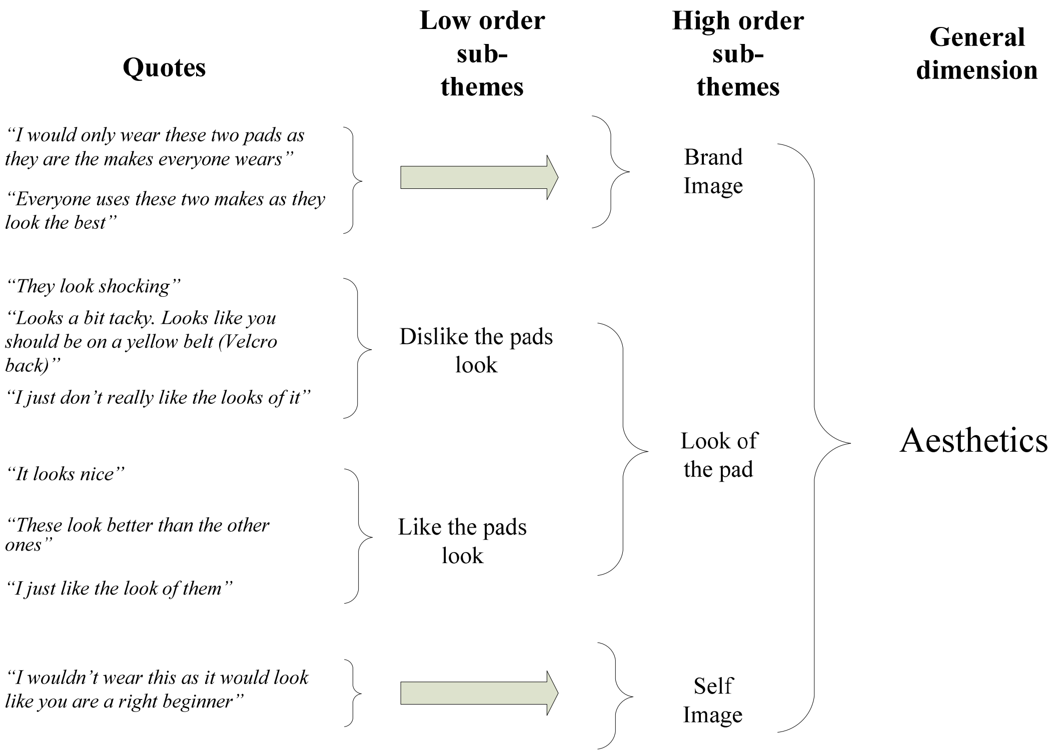


Figure 2. 25: General Dimension of 'Aesthetics' for taekwondo

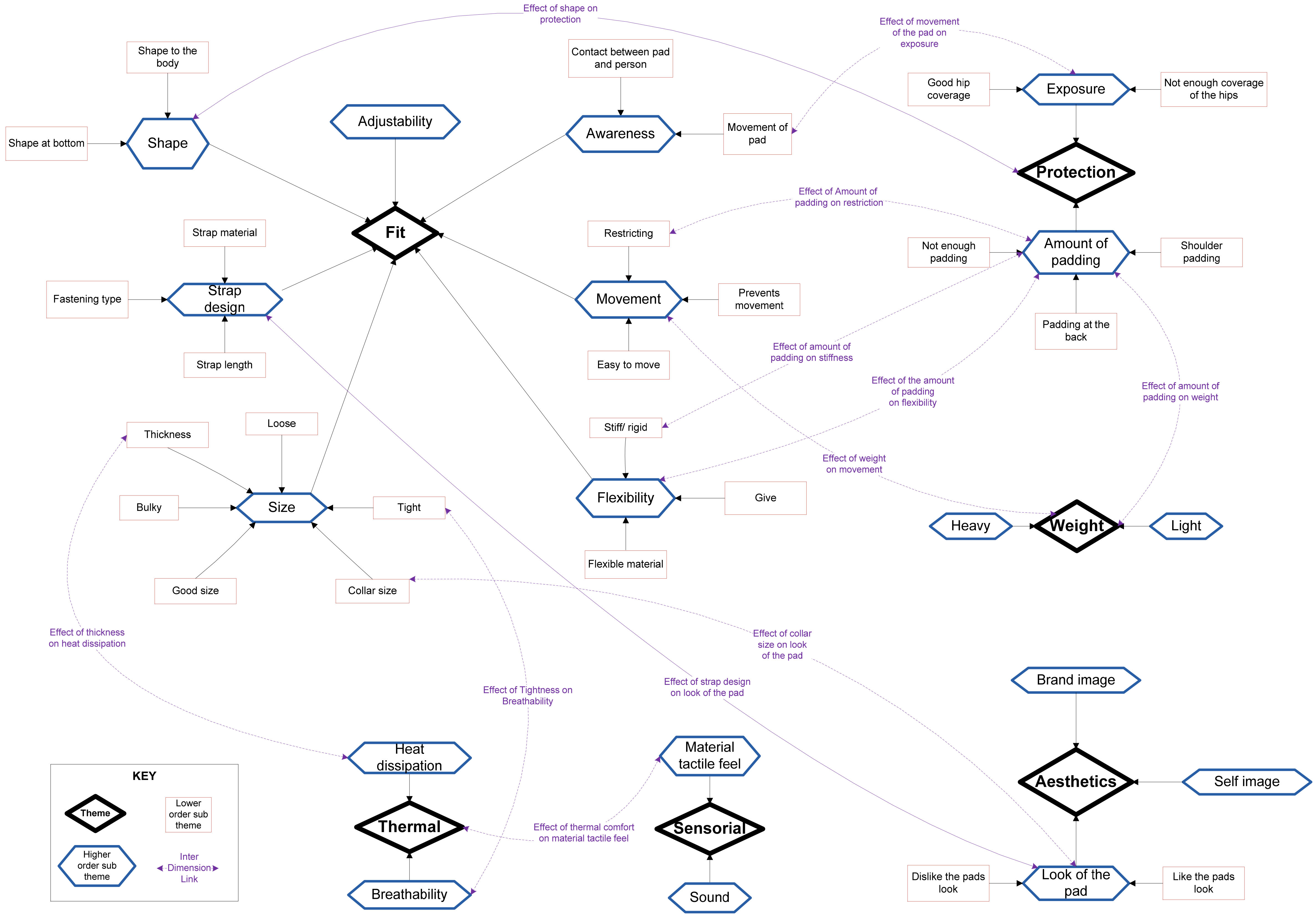


Figure 2. 26: Structured Relationship model for comfort of a taekwondo hogu

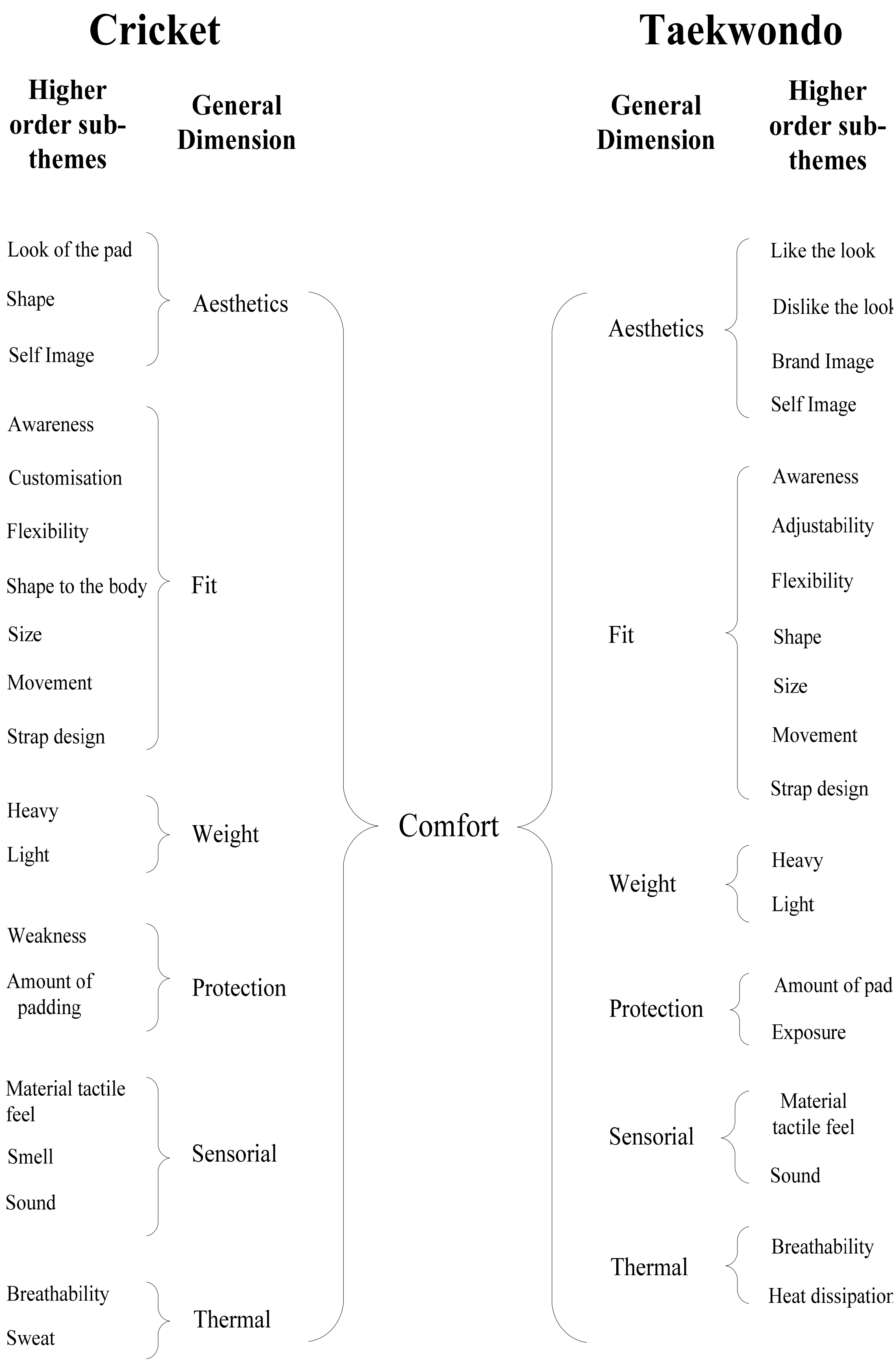


Figure 2. 27: Comparison of general dimensions and higher order sub-themes for cricket and taekwondo

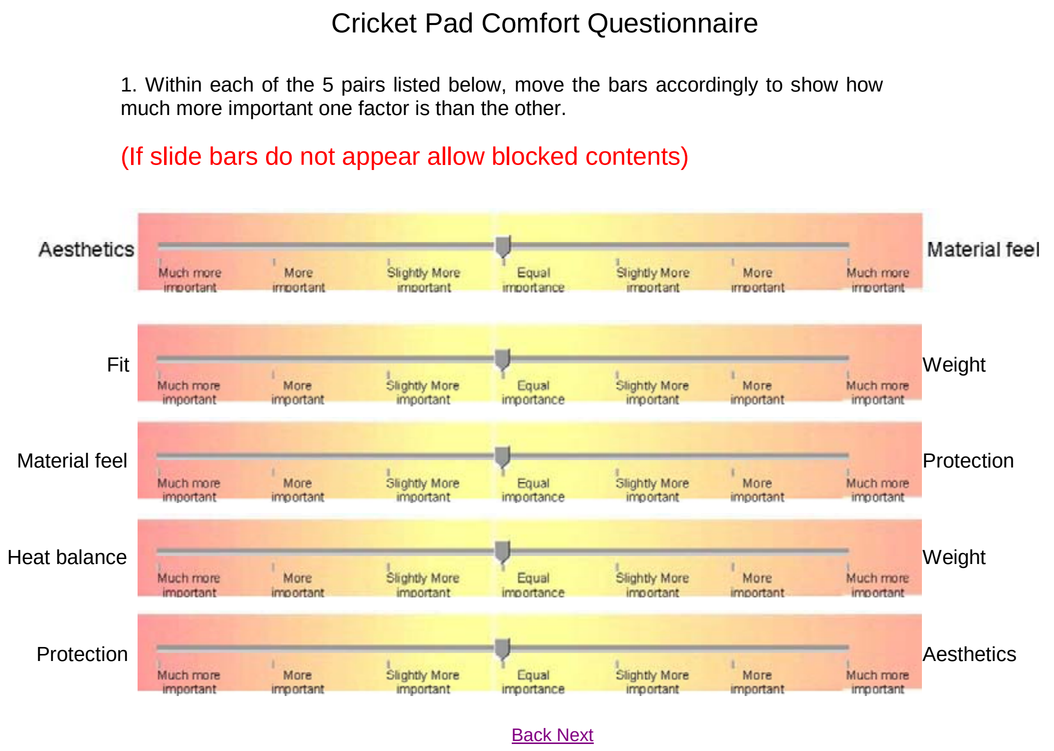


Figure 3. 1: Example question and response bars used within the AHP online questionnaire

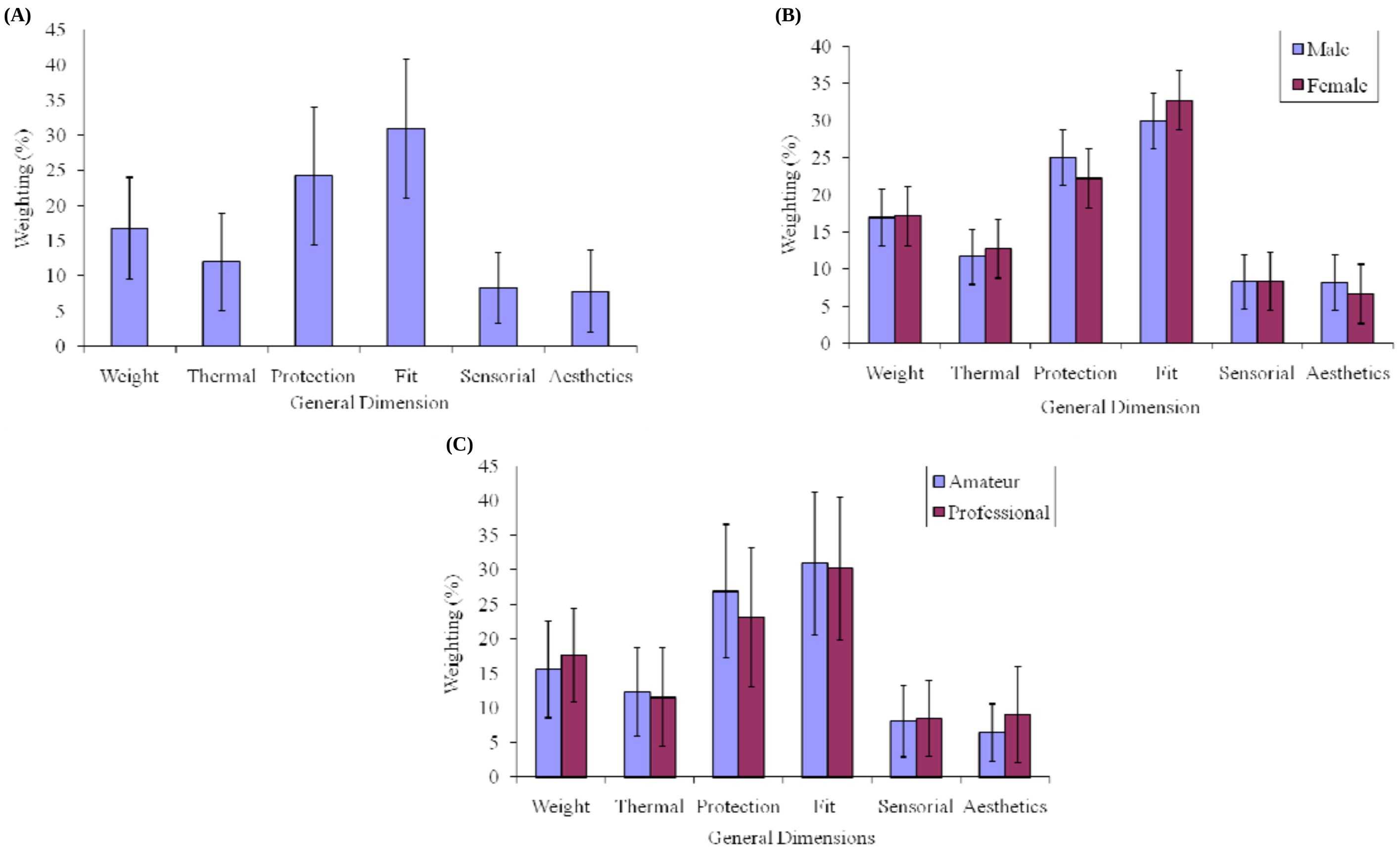


Figure 3. 2: Mean weighting of importance for all six general dimensions attained from the AHP process (A) Combined results for all 100 respondents ±SD, (B) Comparison of Male and Female responses ±SD, and (C) Comparison of Amateur and Professional responses ±SD

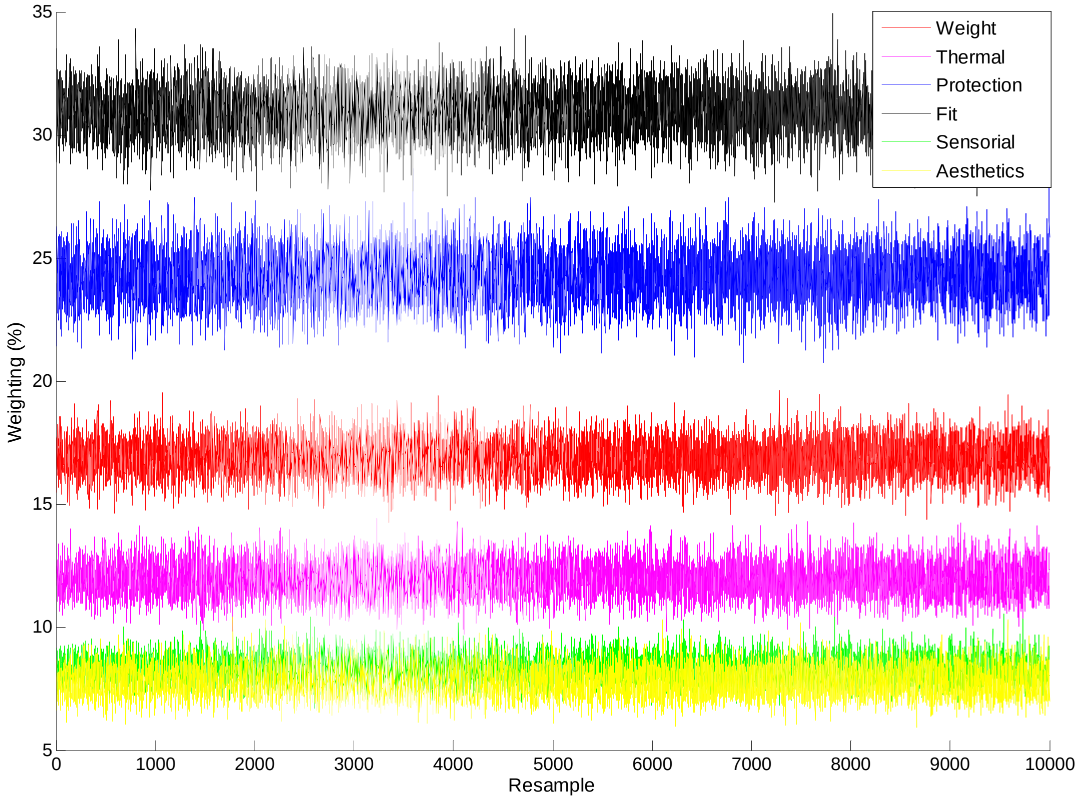


Figure 3. 3: Bootstrap results for 10,000 resamples for the cricket leg guard

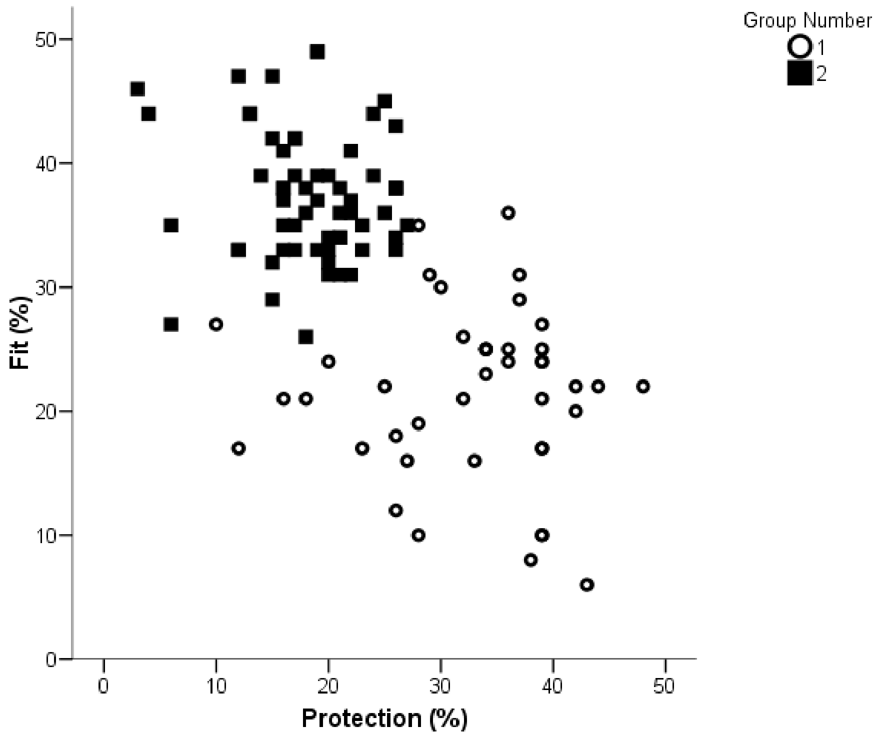


Figure 3. 4: A comparison of weightings assigned to fit and protection between group 1 and 2 of the respondents

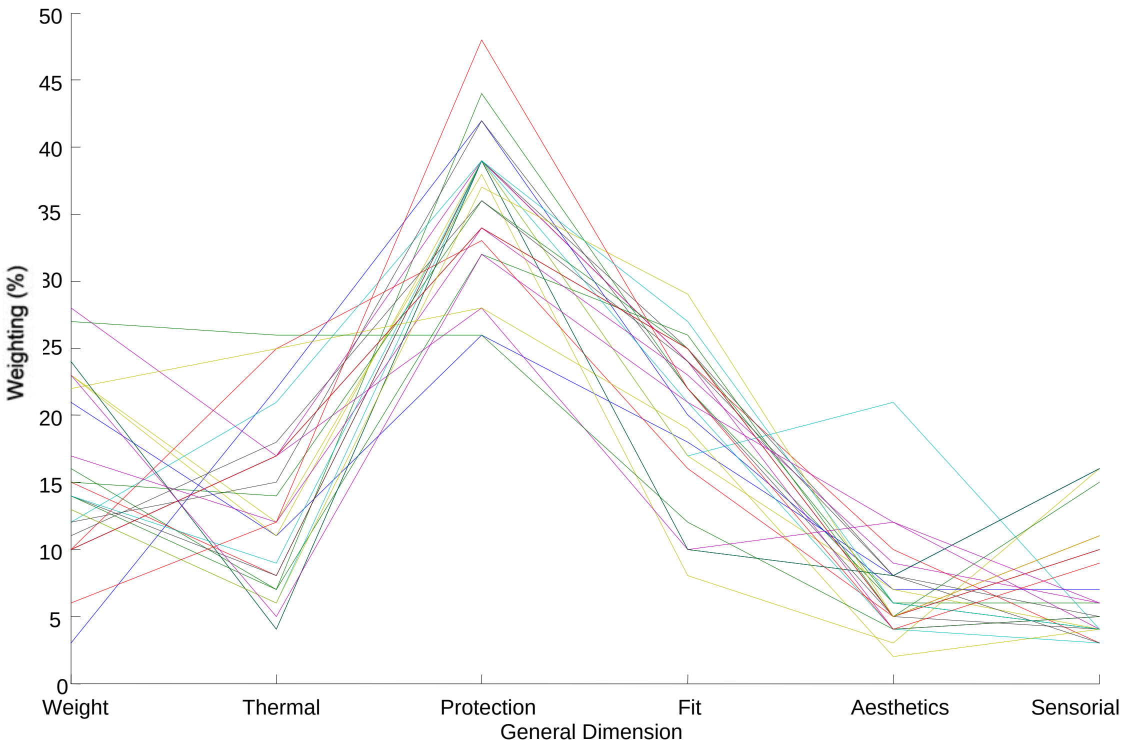


Figure 3. 5: Individual weightings for members of group 1 for all general dimensions for cricket

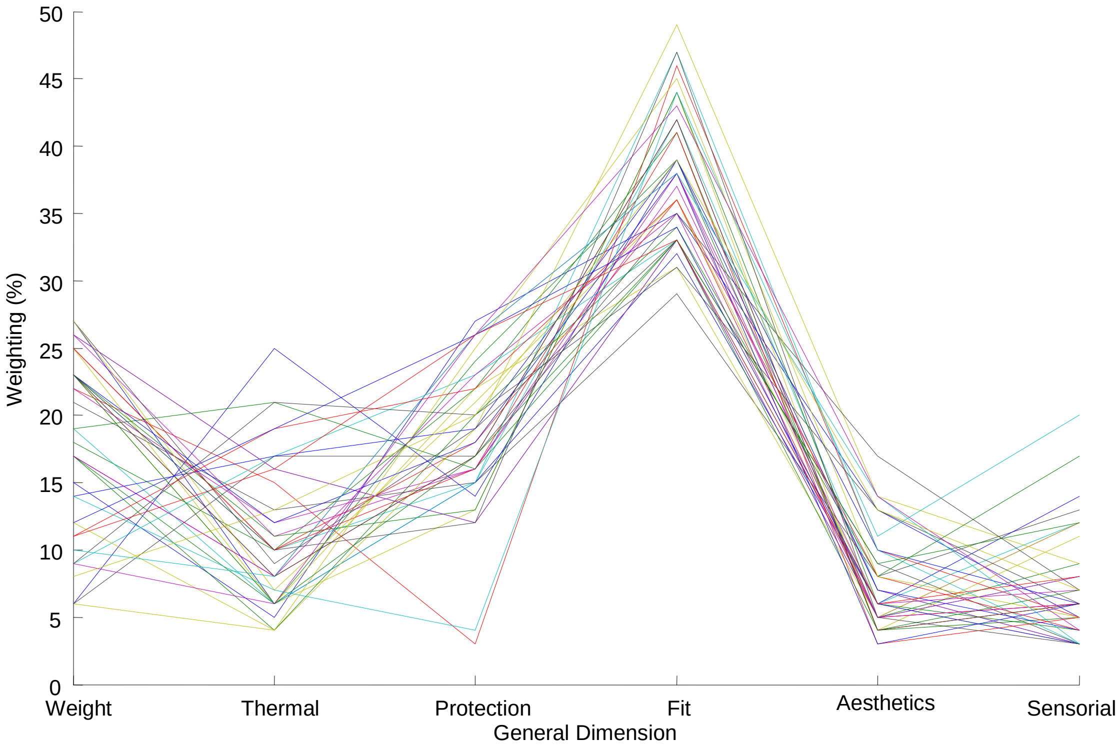


Figure 3. 6: Individual weightings for members of group 2 for all general dimensions for cricket

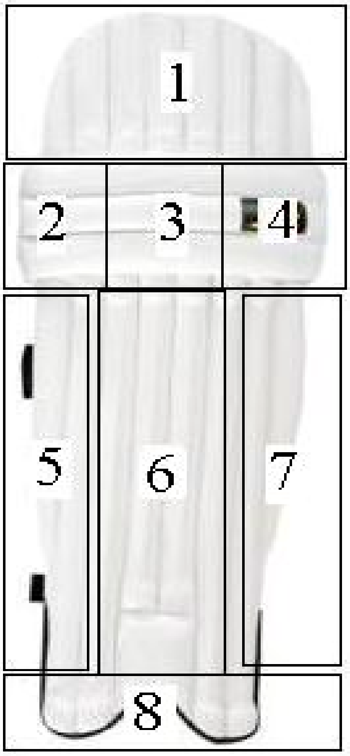


Figure 3. 7: Location of the eight zones assessed within the cricket questionnaire to determine where players perceive the greatest need for protection

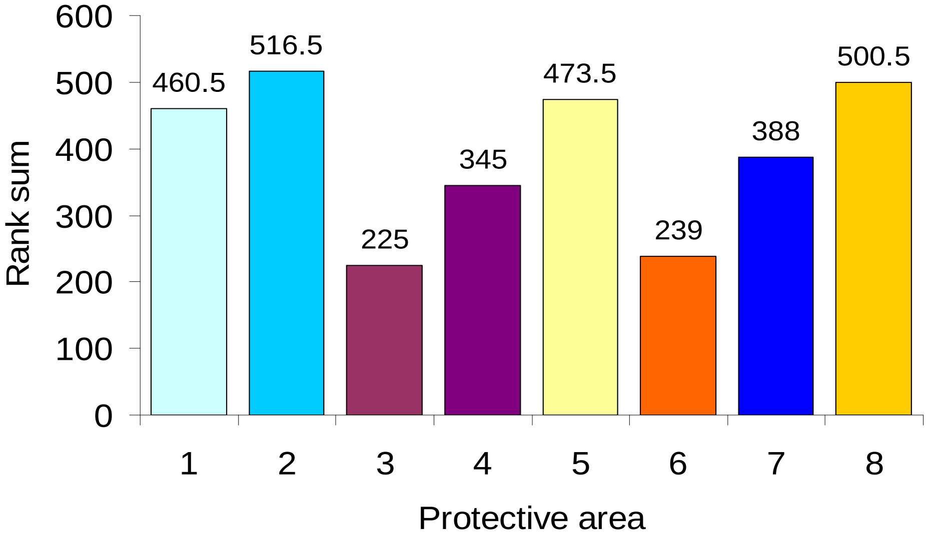


Figure 3. 8: Rank sums for all eight zones regarding where the most protection is required for the cricket leg guard

	Overall shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good
	Overall shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good
	Overall shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good
	Overall shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good

Figure 3. 9: Section 2 question 2, aesthetics assessment

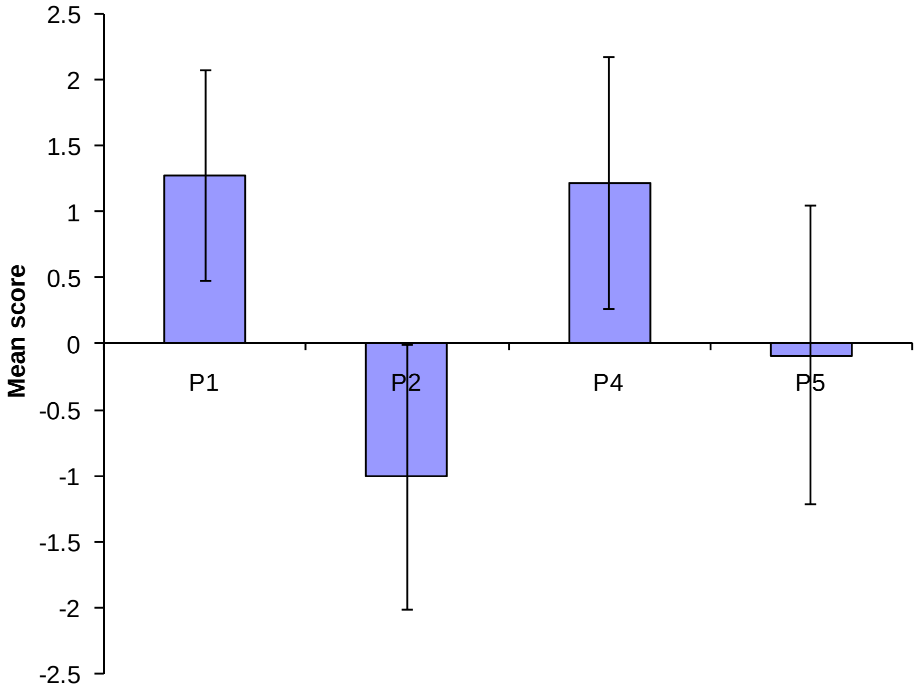


Figure 3. 10:Mean rating of cricket leg guards for the overall shape ±1 standard deviation

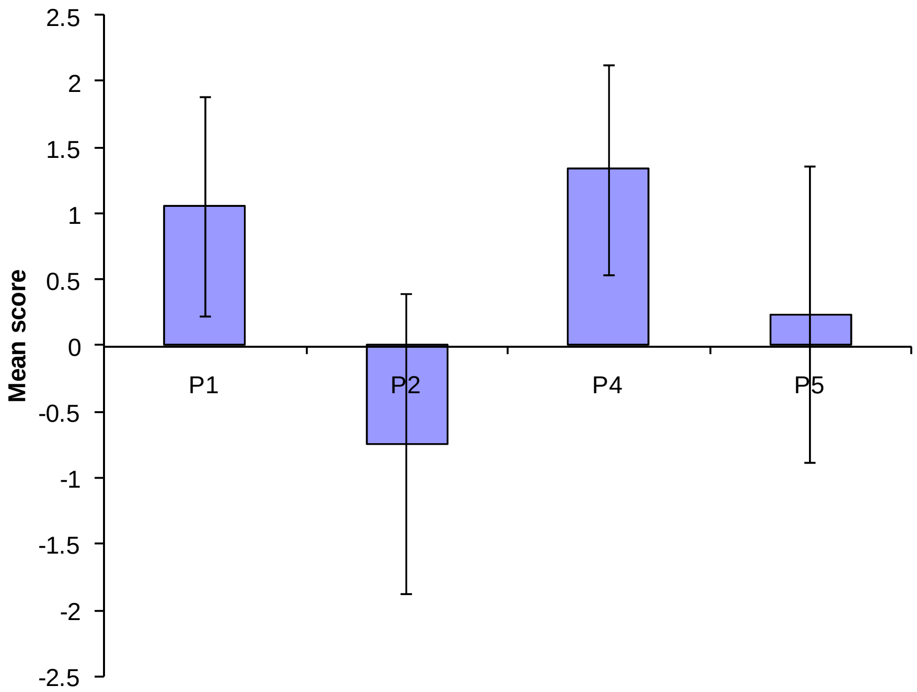


Figure 3. 11: Mean rating of cricket leg guards for the area above the knee ±1 standard deviation

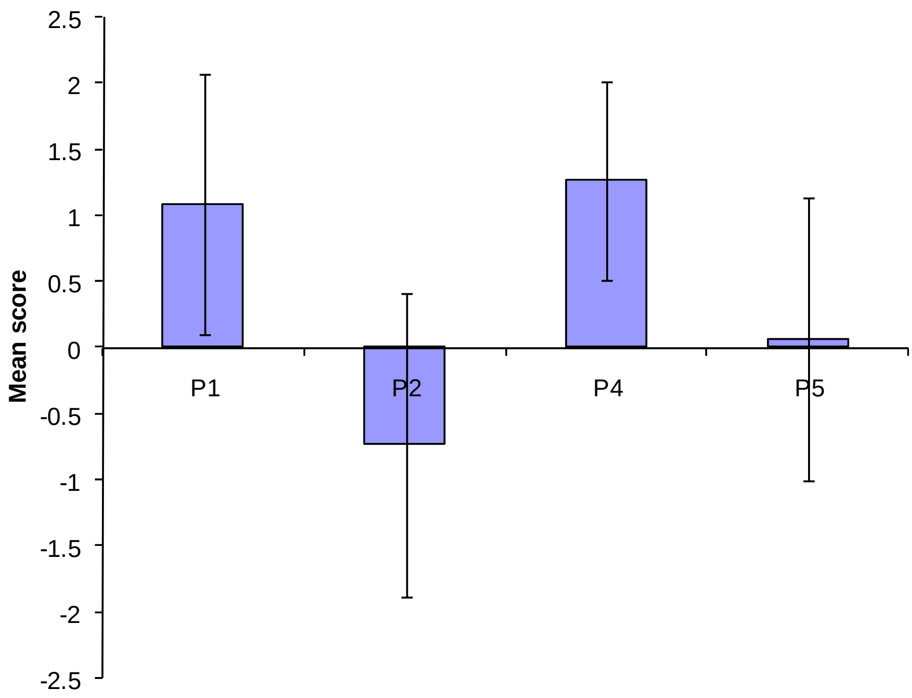


Figure 3. 12: Mean rating of cricket leg guards A-D for the knee area ±1 standard deviation

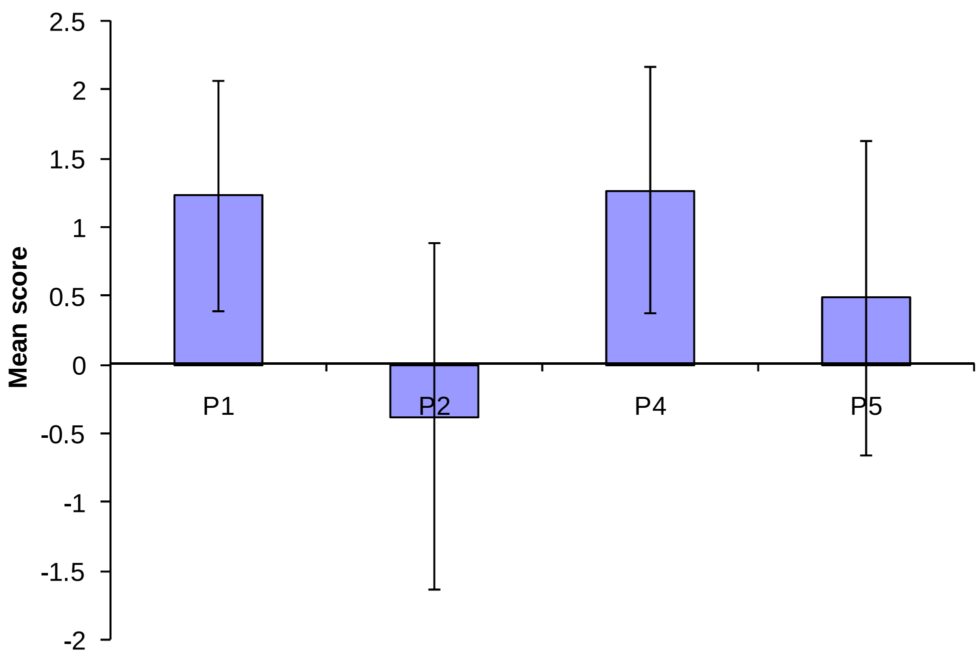


Figure 3. 13: Mean rating of cricket leg guards for the shin area ±1 standard deviation

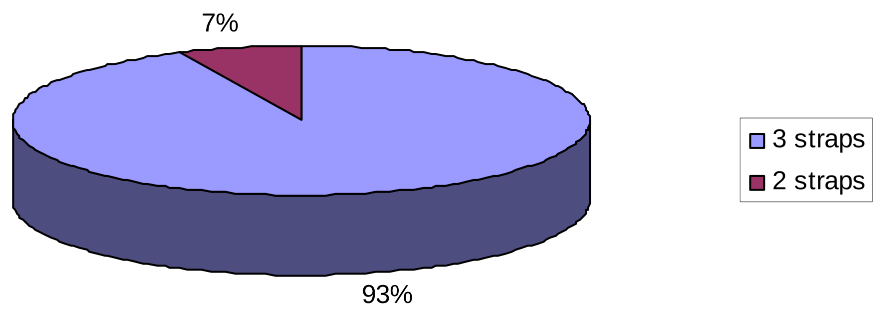


Figure 3. 14: Preference for cricket leg guards with two or three straps

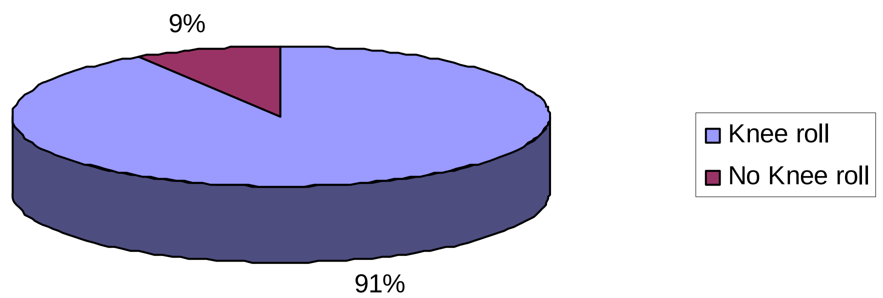


Figure 3. 15: Preference for cricket leg guards with or without a knee roll

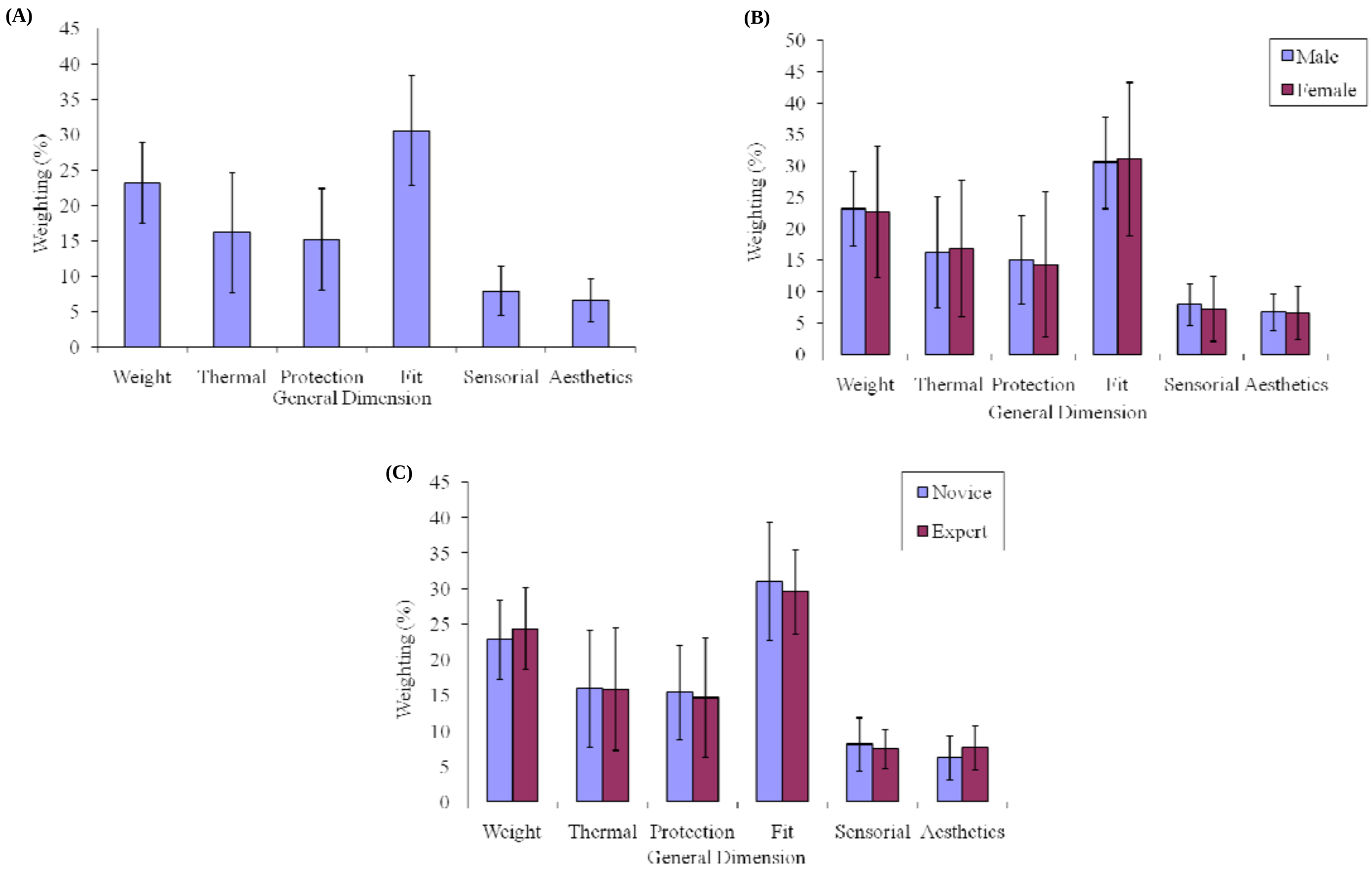


Figure 3. 16: Mean weighting of importance for all six general dimensions attained from the AHP process for taekwondo (A) Combined results for all 43 respondents ±SD, (B) Comparison of Male and Female responses ±SD, and (C) Comparison of expert and novice responses

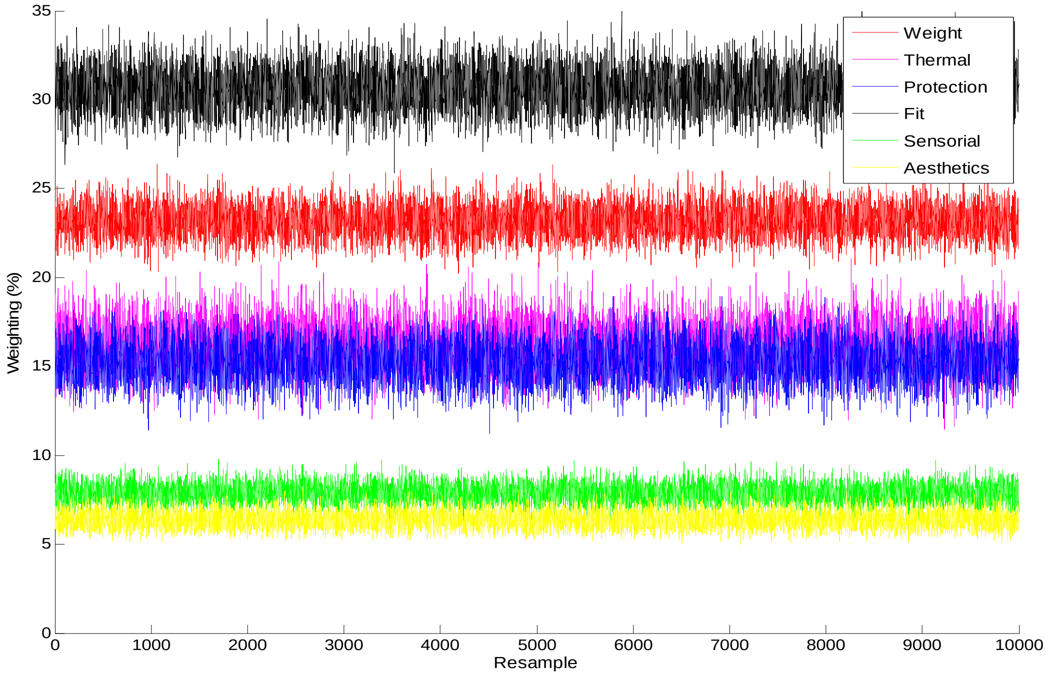


Figure 3. 17: Bootstrap results for 10,000 resamples for the taekwondo hogu

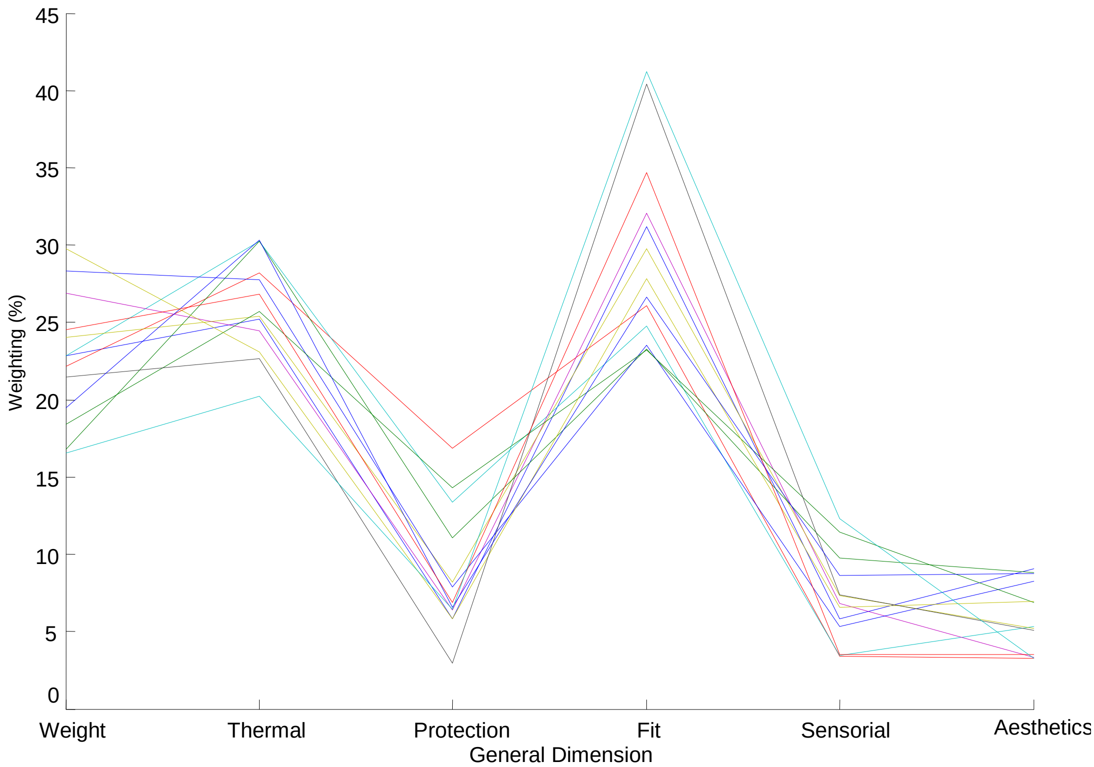


Figure 3. 18: Individual weightings for members of group 1 for all general dimensions for taekwondo

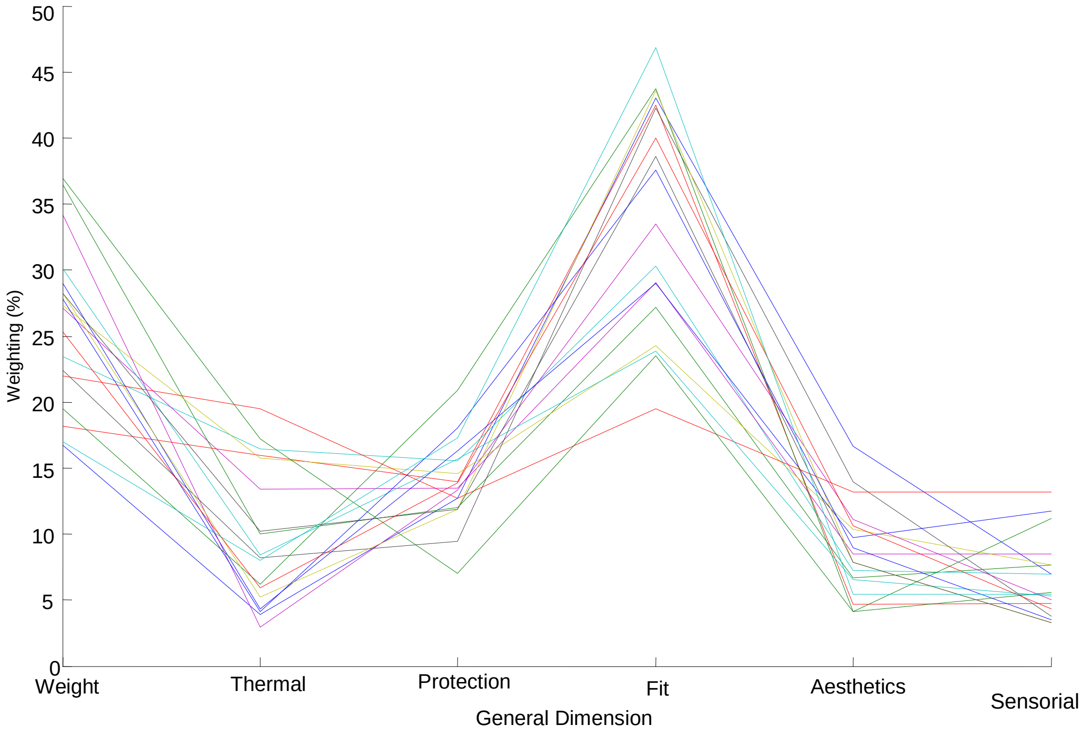


Figure 3. 19: Individual weightings for members of group 2 for all general dimensions for taekwondo

Figure 3. 20: Location of the 6 zones assessed within the taekwondo questionnaire for where players perceive there to be the greatest need for protection

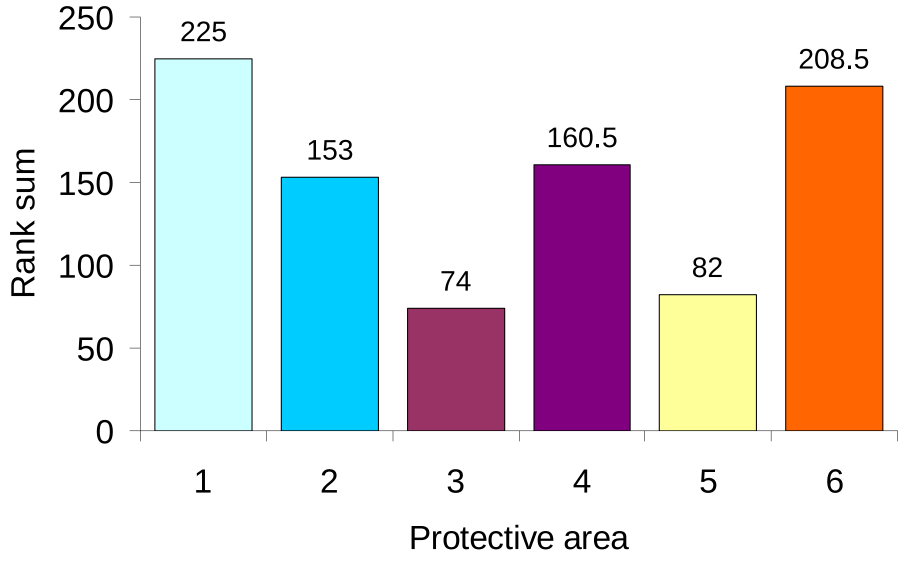


Figure 3. 21: Rank sum for all 6 zones regarding where the most protection is required for the taekwondo hogu

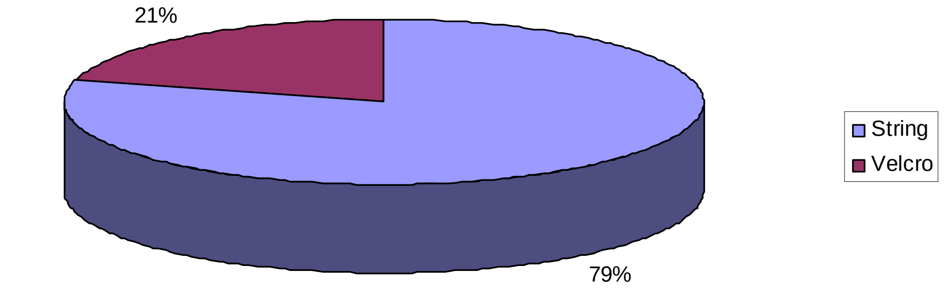


Figure 3. 22: Preference for taekwondo hogus with Velcro or string straps

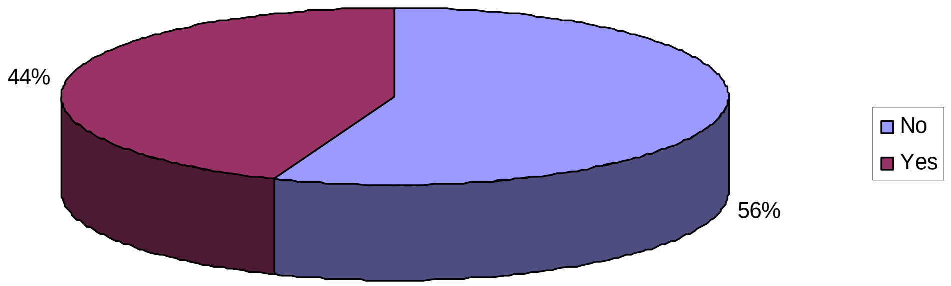


Figure 3. 23: Assessment of whether hogu users perceive the pad to rub and irritate the neck

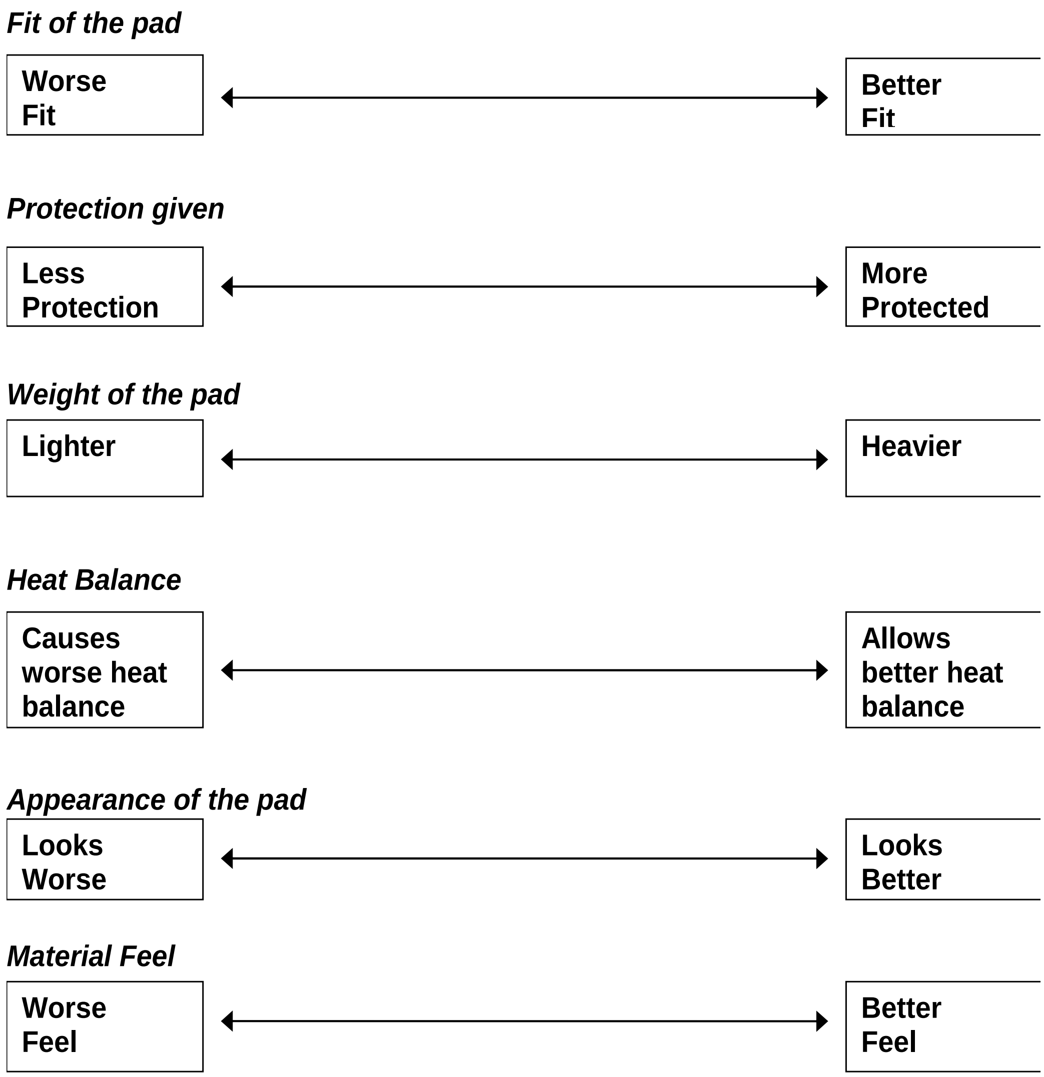


Figure 3. 24: Example of model validation scales used

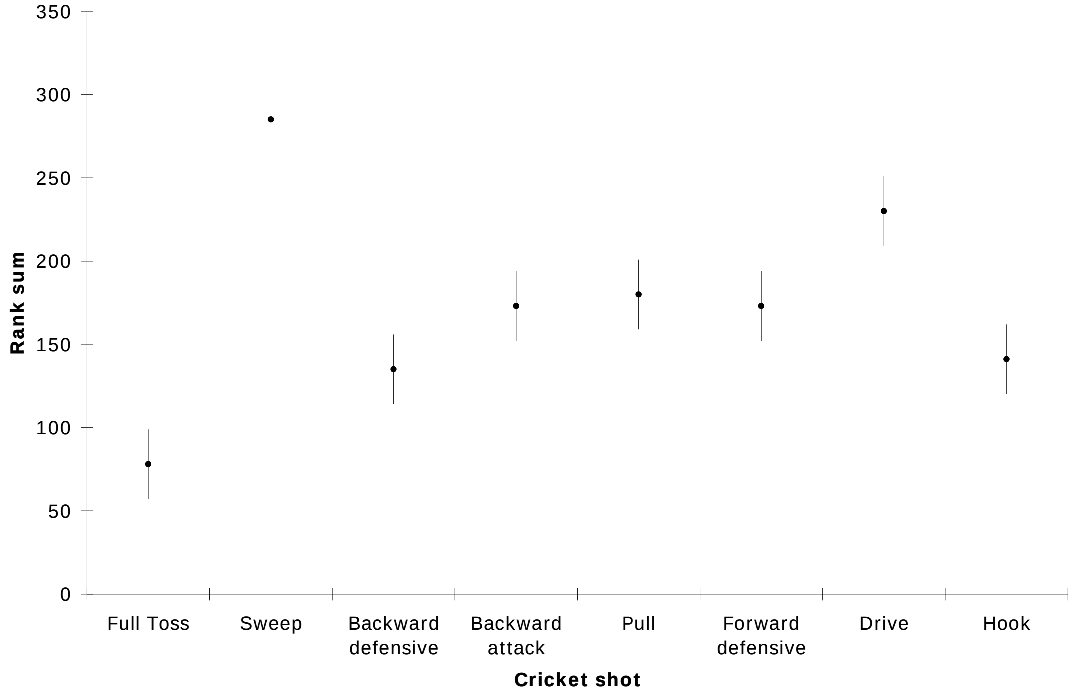


Figure 4. 1: Rank sum ±1/2 LSD_{rank} of perceived restriction caused by cricket pads for different shots

Figure 4. 2: Example of experimental set up for the pull shot

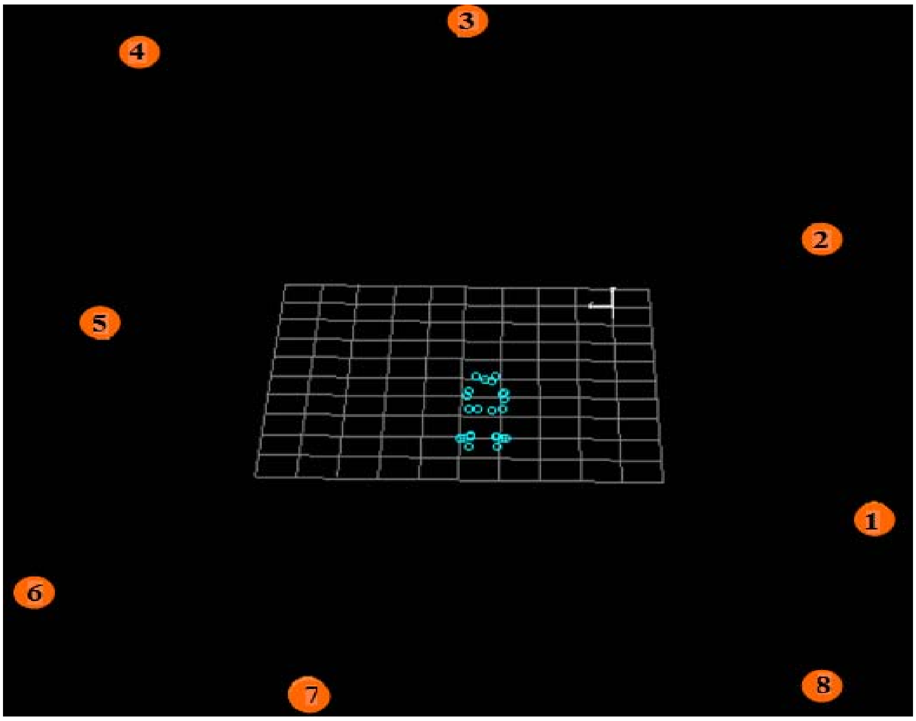


Figure 4. 3: Camera position relative to subject batting position

Figure 4. 4: Vicon head unit (Vicon, 2010)

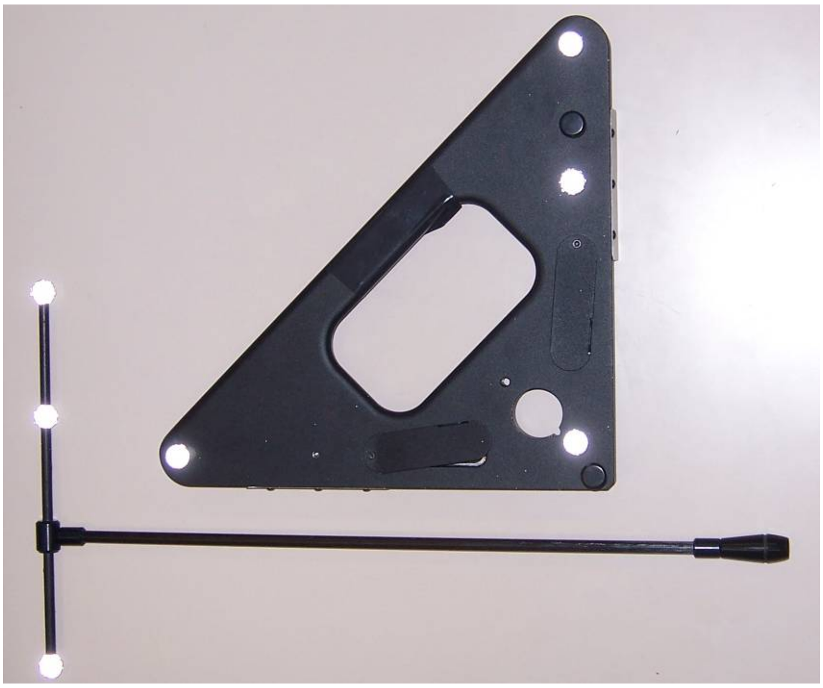


Figure 4. 5: Ergocal calibration frame and wand

Figure 4. 6: Redundant marker set

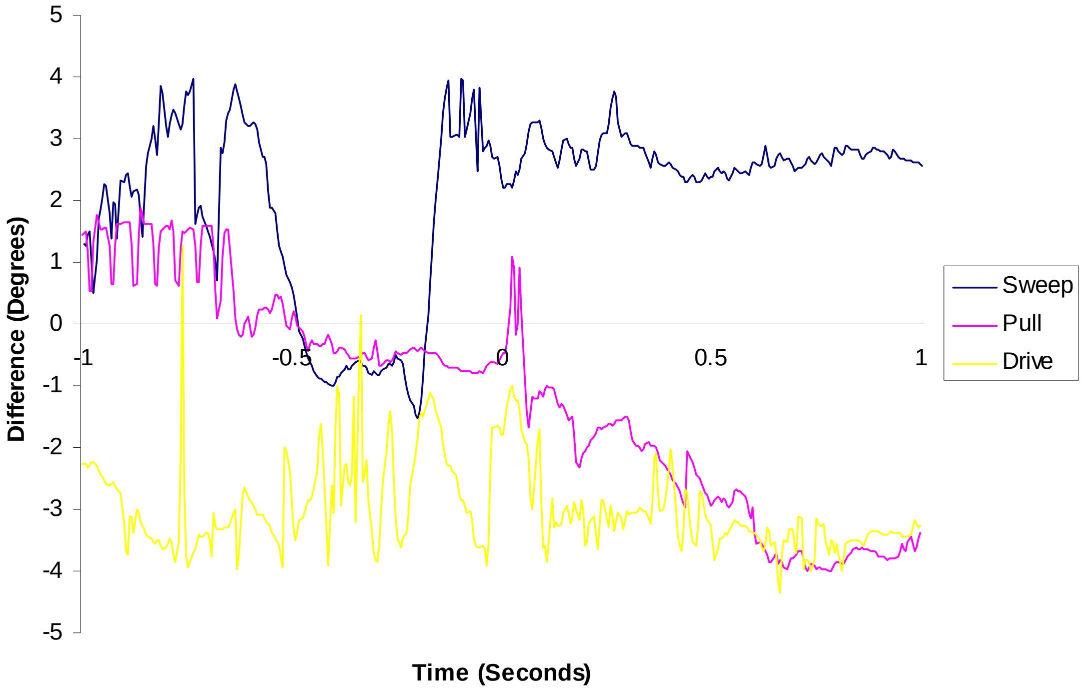


Figure 4. 7: Differences in joint angles calculated from cluster markers and markers on anatomical landmarks for one NP trial for all three types of shot

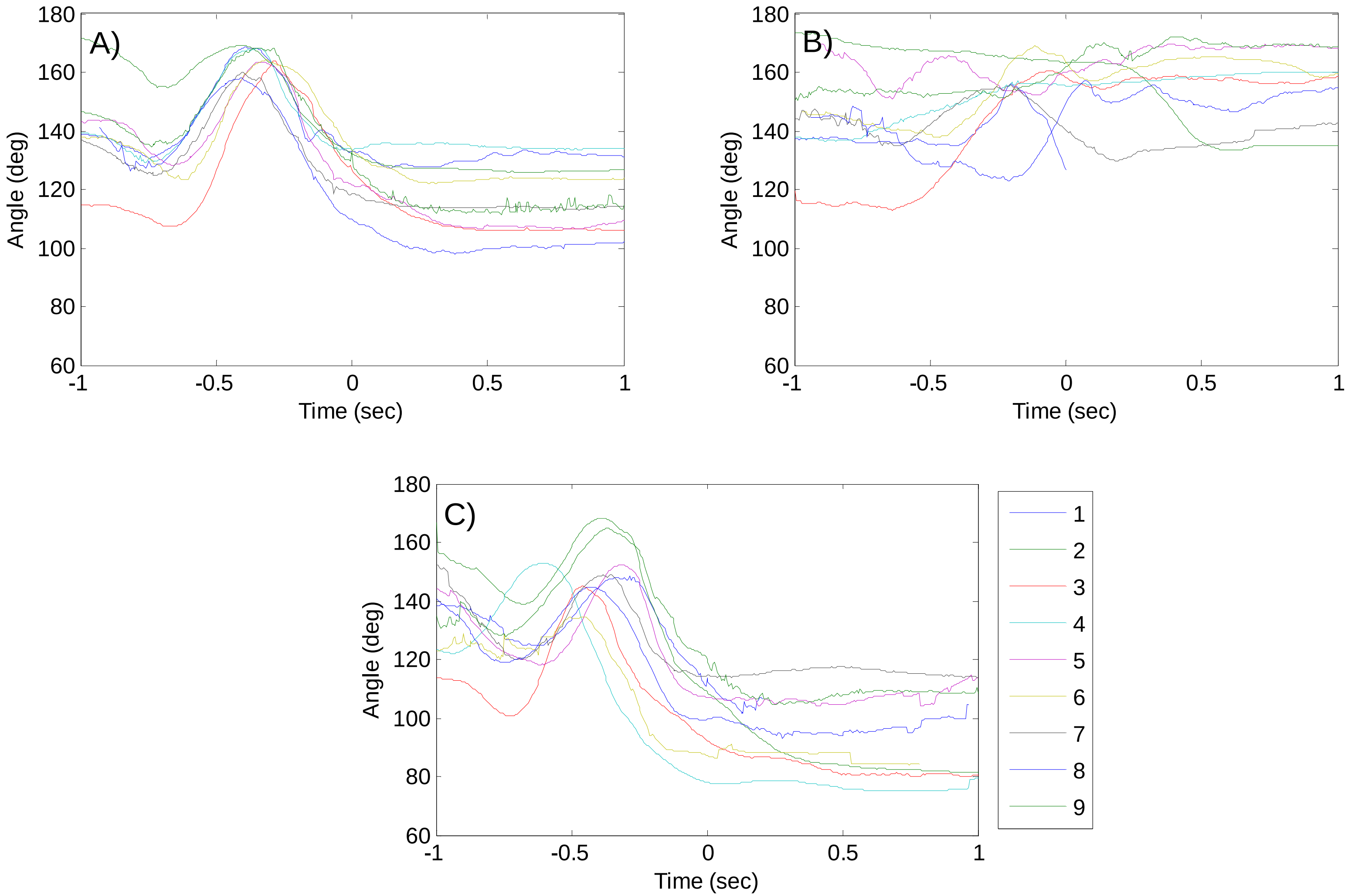


Figure 4. 8: Comparison of all 9 participants mean LKA from 1 second before impact to 1 second post impact whilst wearing no pads, for the A) drive, B) pull and C) sweep

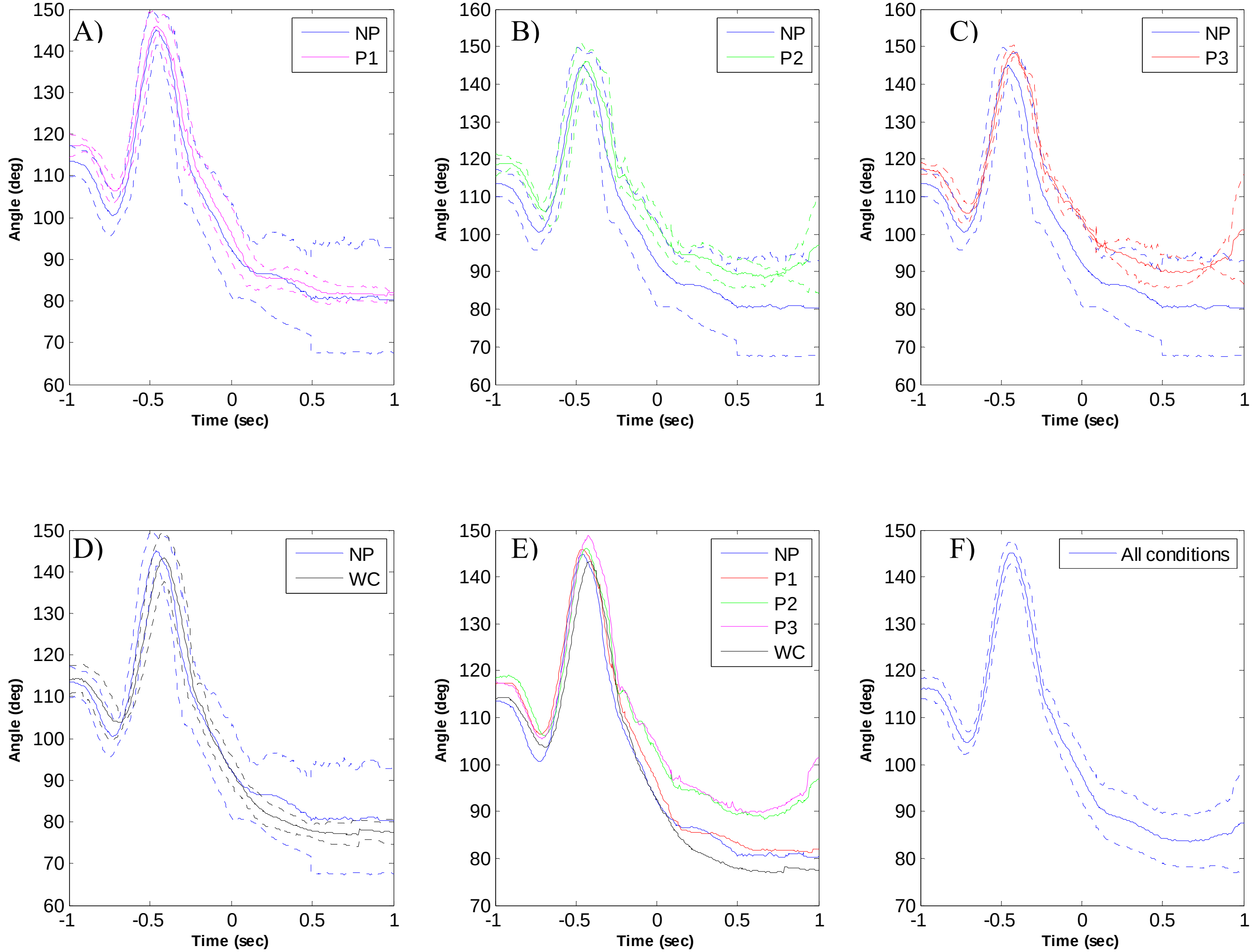


Figure 4. 9: Subject 3- LKA comparison between A) NP and P1, B) NP and P2, C) NP and P3, D) NP and WC, E) mean angles for all conditions, F) Mean and standard deviation across the 5 conditions for the sweep

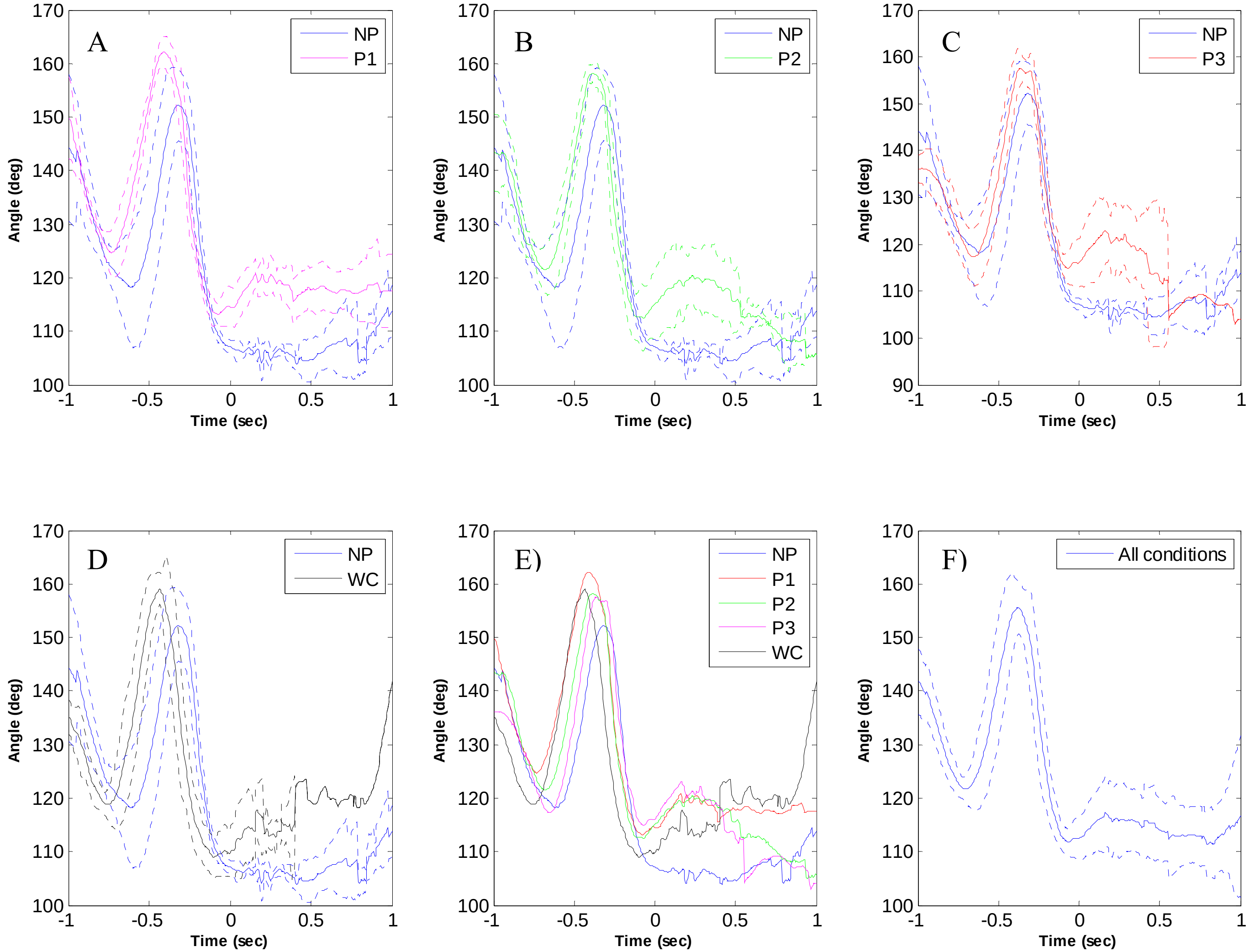


Figure 4. 10: Subject 5- LKA comparison between A) NP and P1, B) NP and P2, C) NP and P3, D) NP and WC, E) mean angles for all conditions, F) Mean and standard deviation across the 5 conditions for the sweep

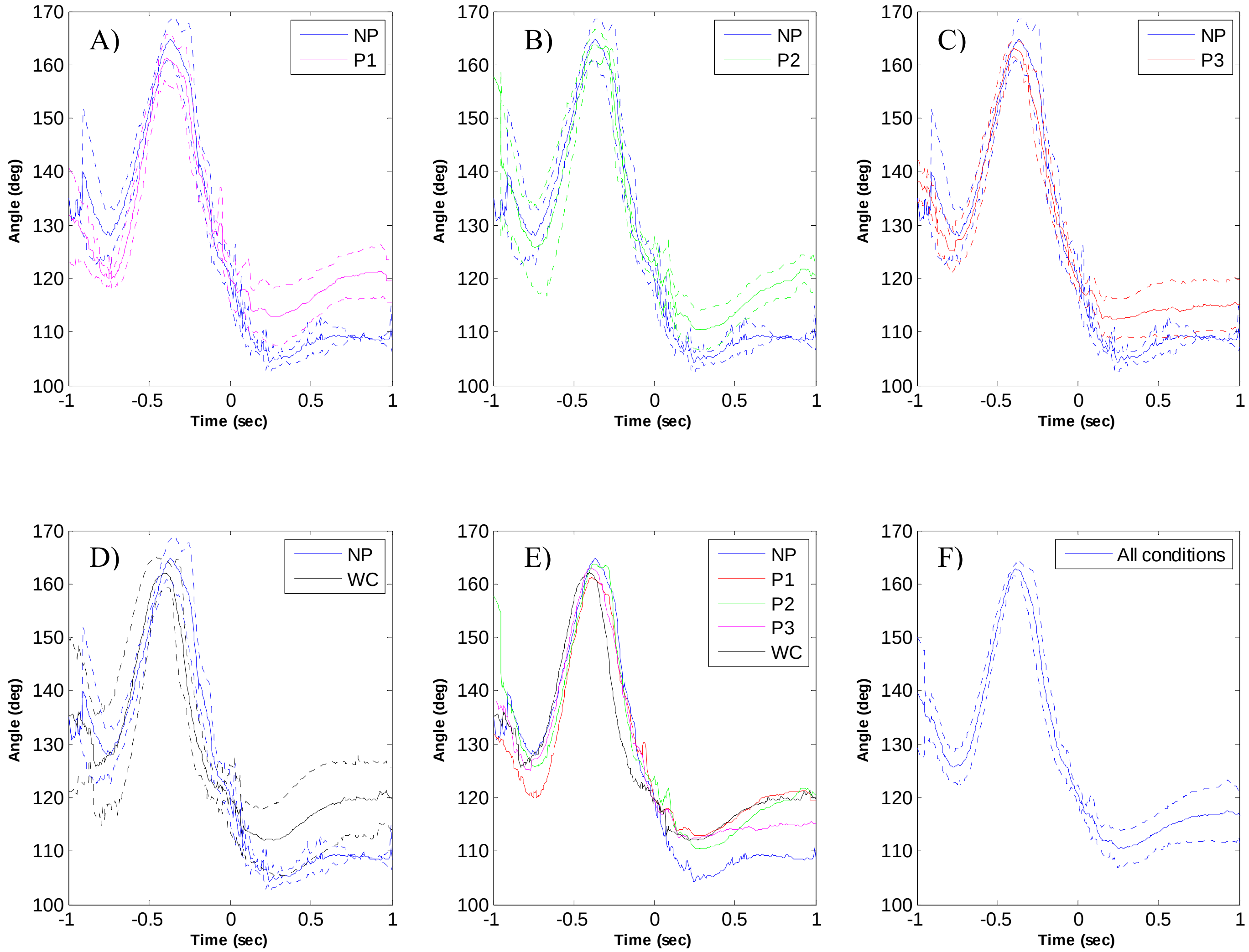


Figure 4. 11: Subject 3- LKA comparison between A) NP and P1, B) NP and P2, C) NP and P3, D) NP and WC, E) mean angles for all conditions, F) Mean and standard deviation across the 5 conditions for the sweep

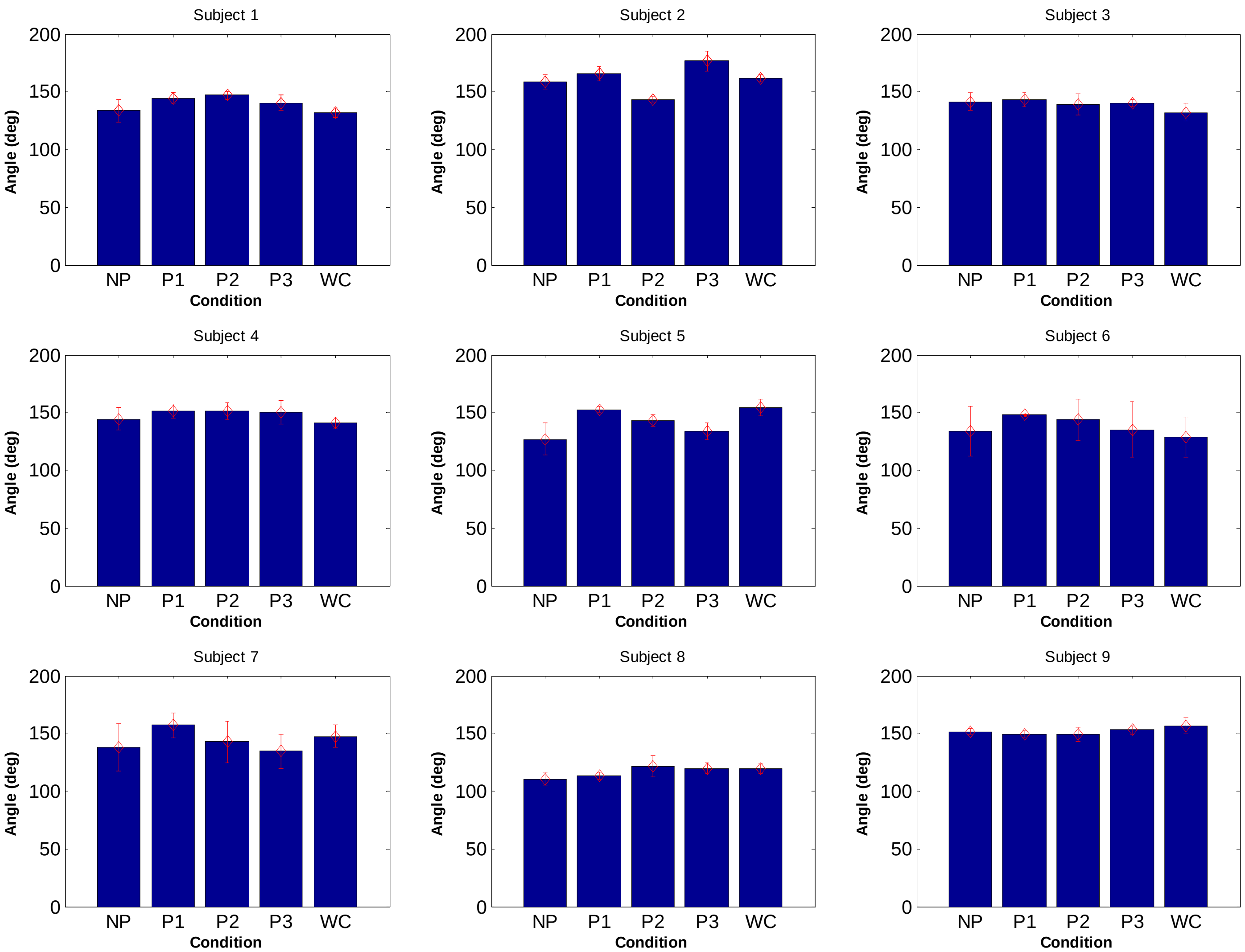


Figure 4. 12: Mean LKA ±1SD for the sweep 0.5seconds before impact for all 9 subjects

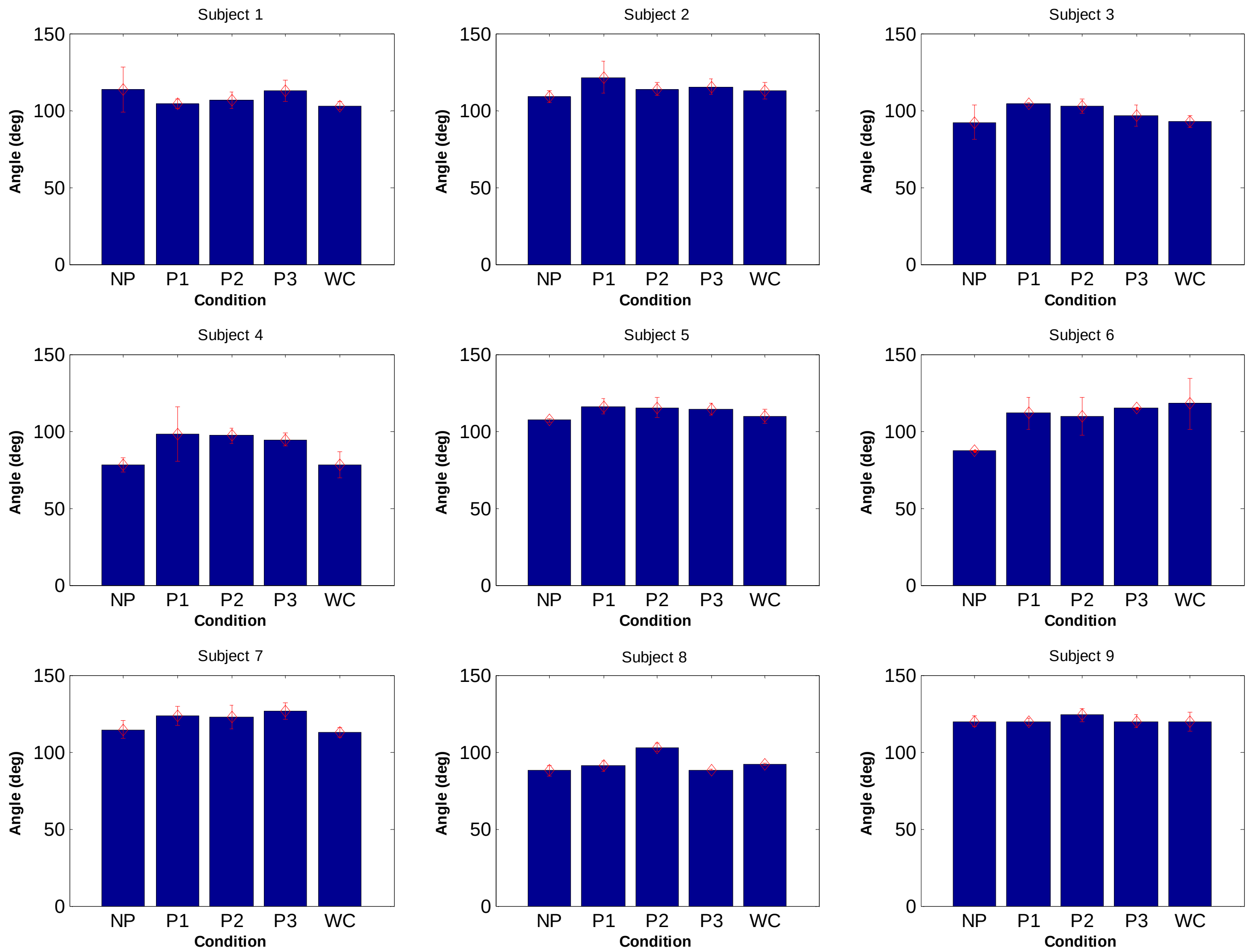


Figure 4. 13: Mean LKA ±1SD for the sweep at impact for all 9 subjects

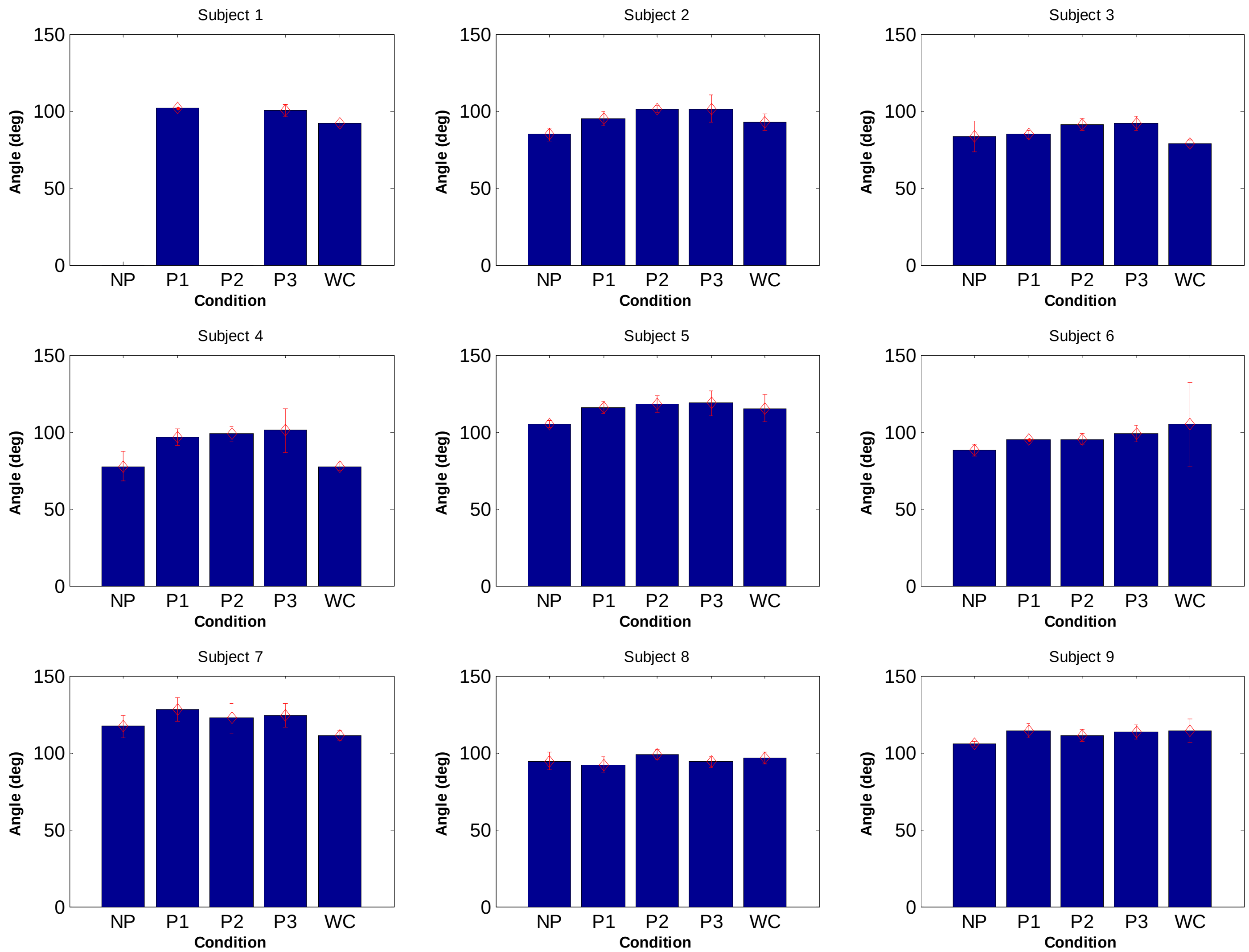


Figure 4. 14: Mean LKA ±1SD for the sweep 0.5seconds after impact for all 9 subjects

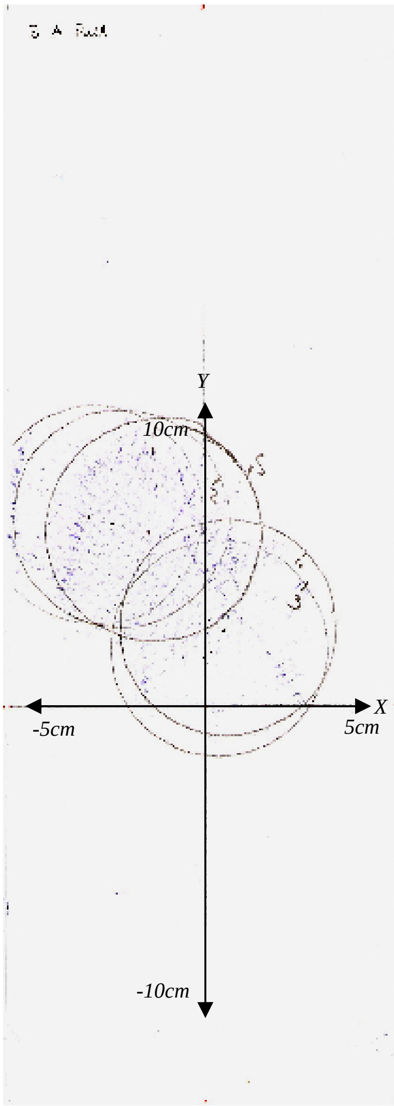


Figure 4. 15: Subject 5 ball impact label for the pull whilst wearing no pads

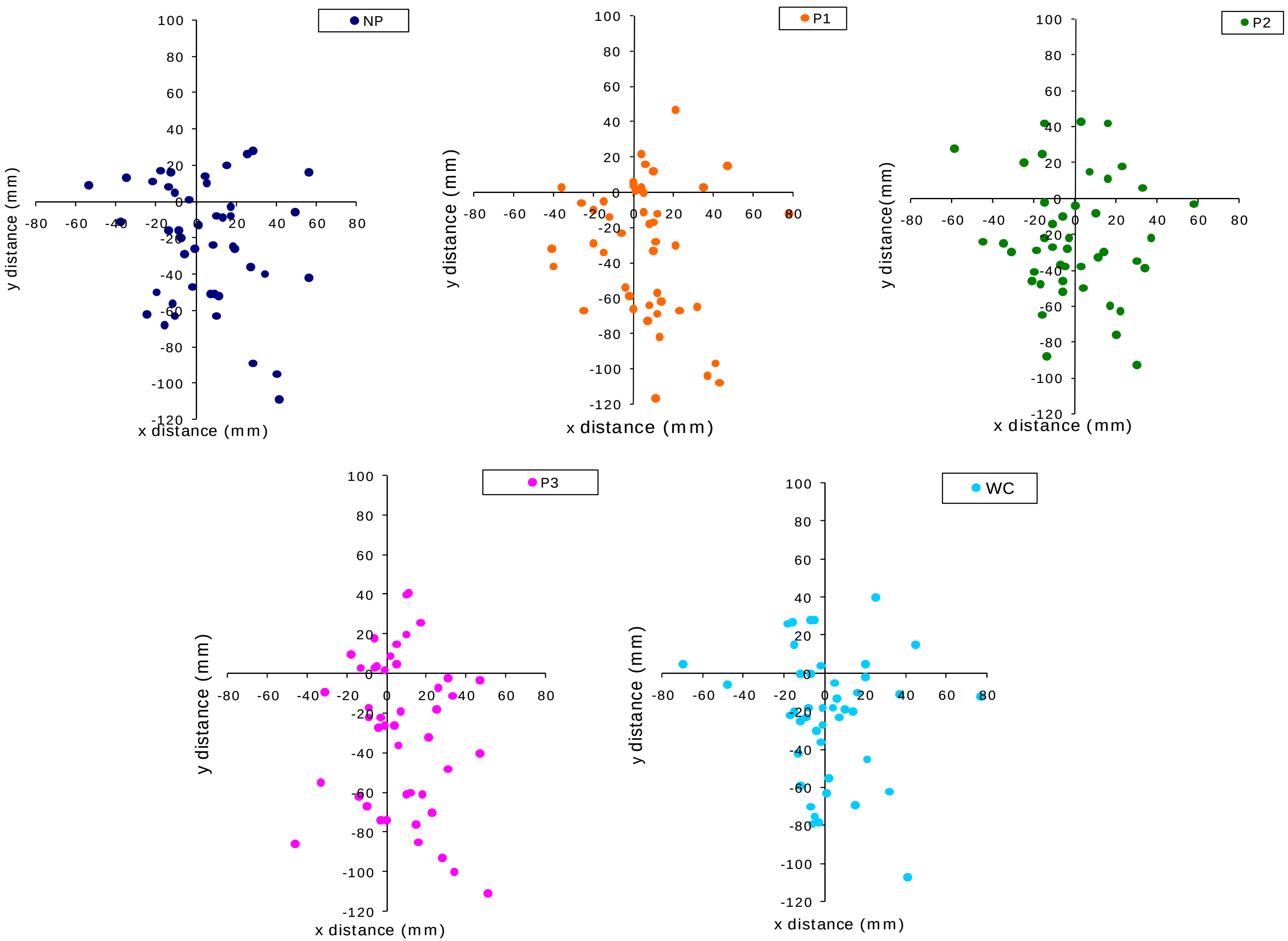


Figure 4. 16: All 45 ball impacts for the sweep

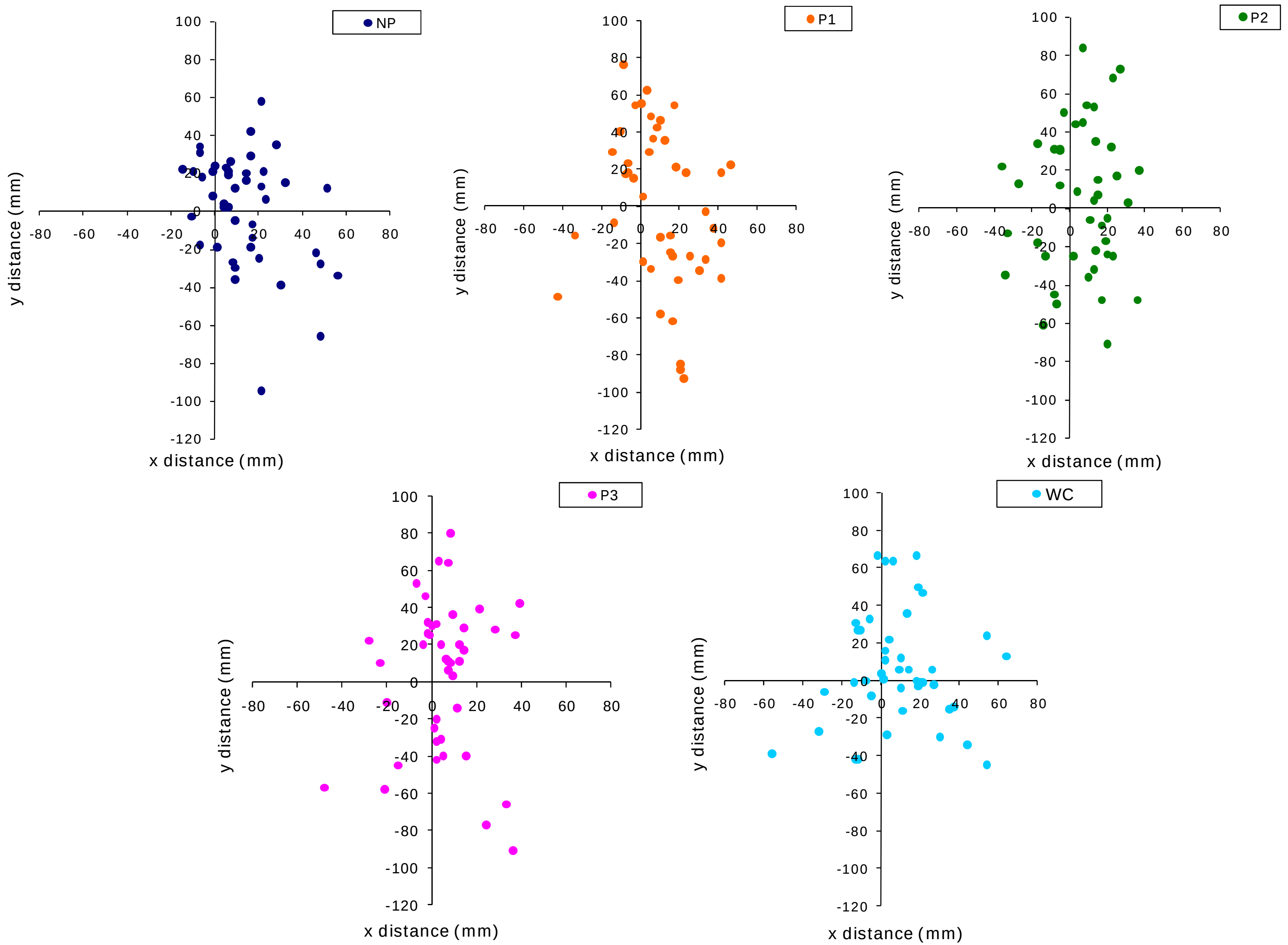


Figure 4. 17: All 45 ball impacts for the drive

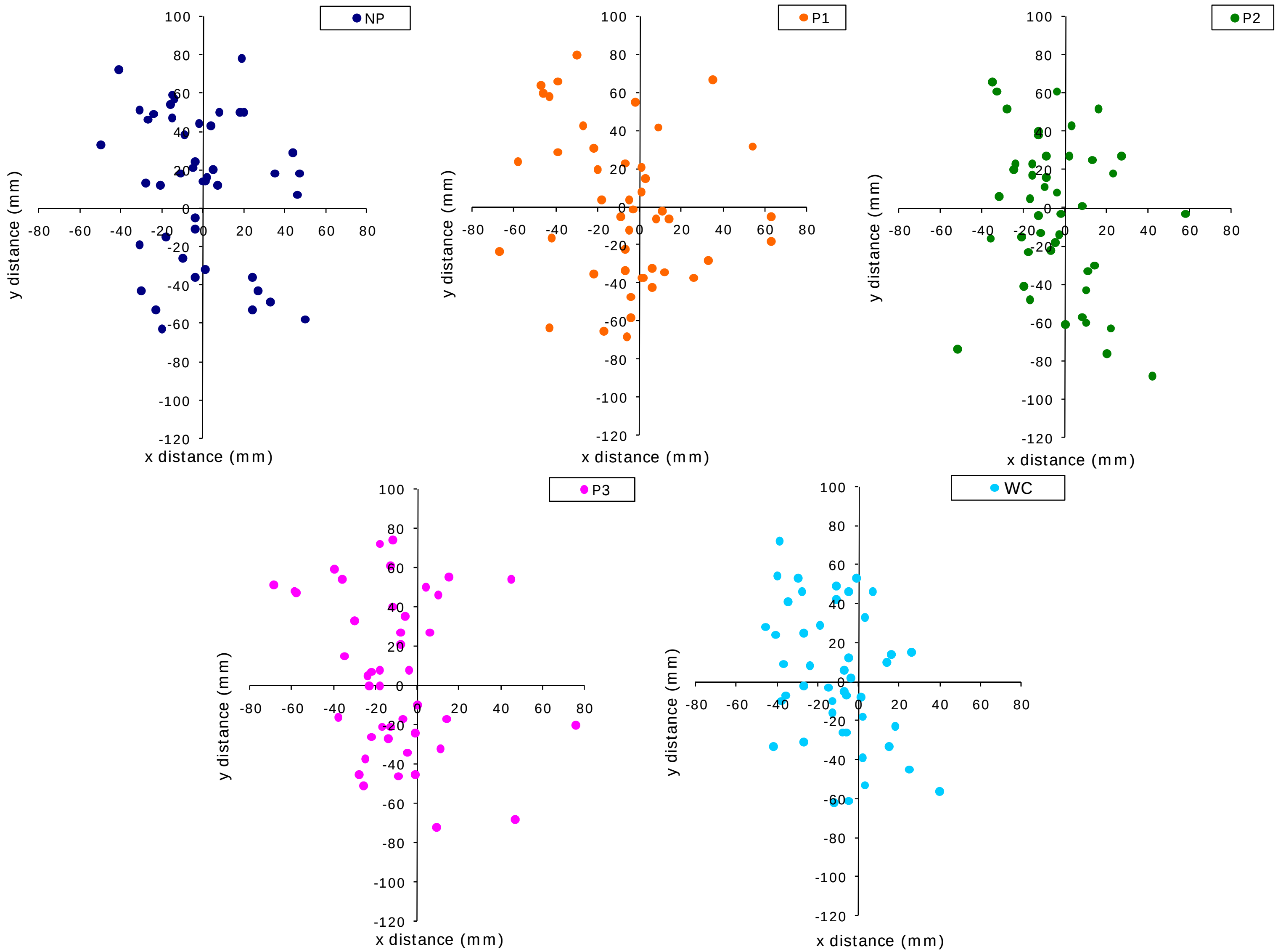


Figure 4. 18: All 45 ball impacts for the pull

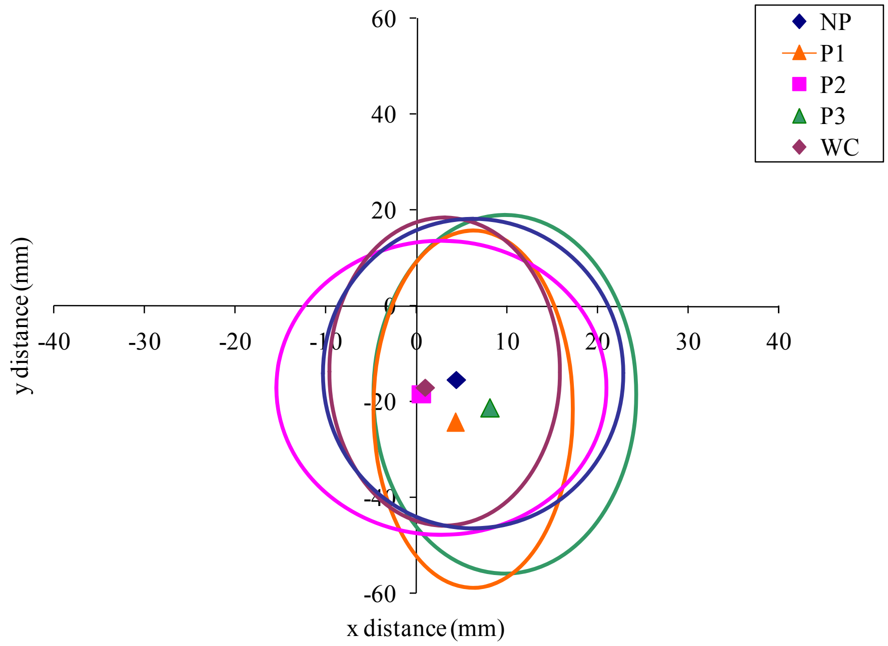


Figure 4. 19: Mean location and confidence ellipse for impact locations of all 5 conditions whilst performing a sweep

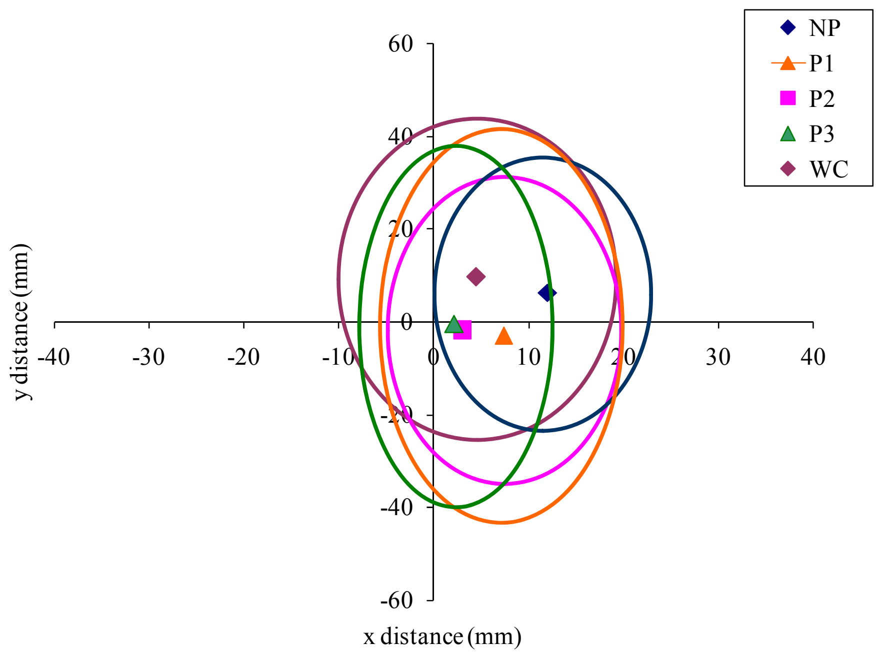


Figure 4. 20: Mean location and confidence ellipse for impact locations of all 5 conditions whilst performing a drive

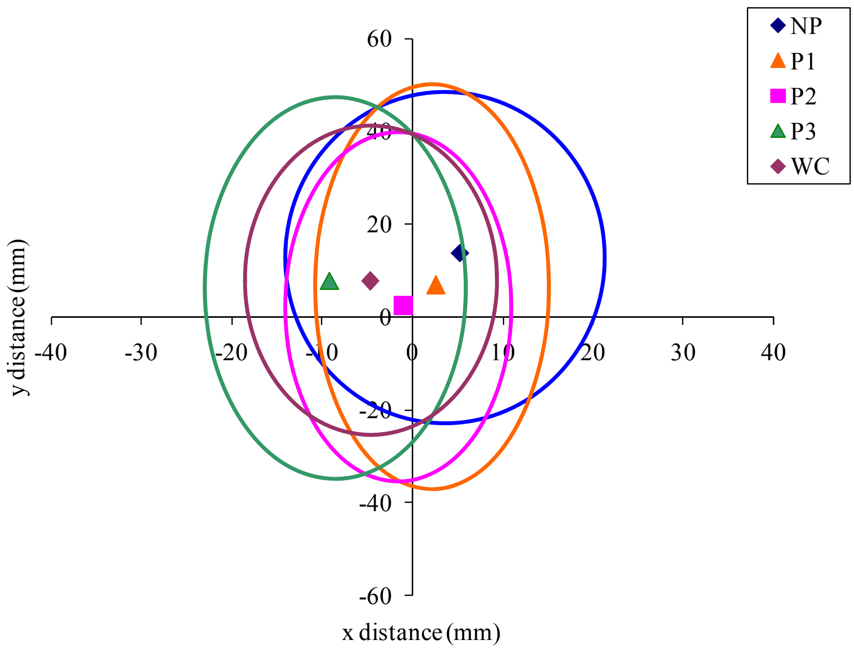


Figure 4. 21: Mean location and confidence ellipse for impact locations of all 5 conditions whilst performing a pull

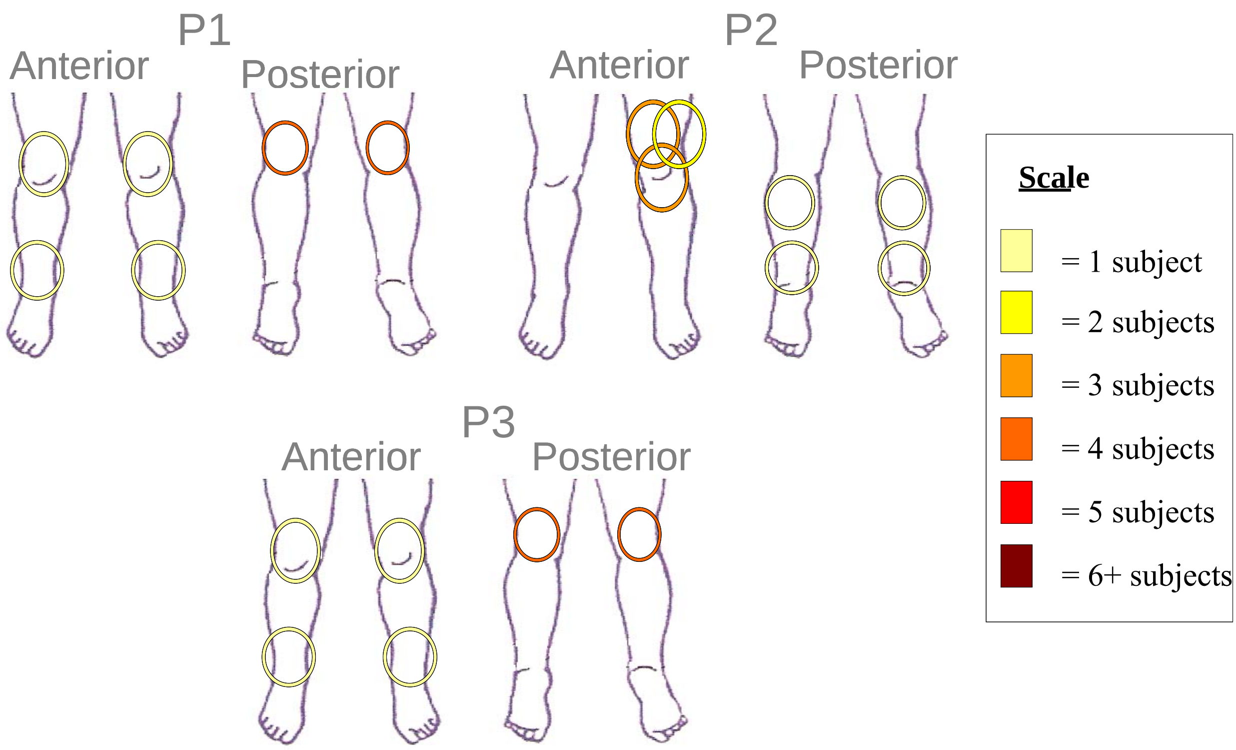


Figure 4. 22:Areas of discomfort identified for P1, P2 and P3

Figure 5. 1: Smart speed timing gate

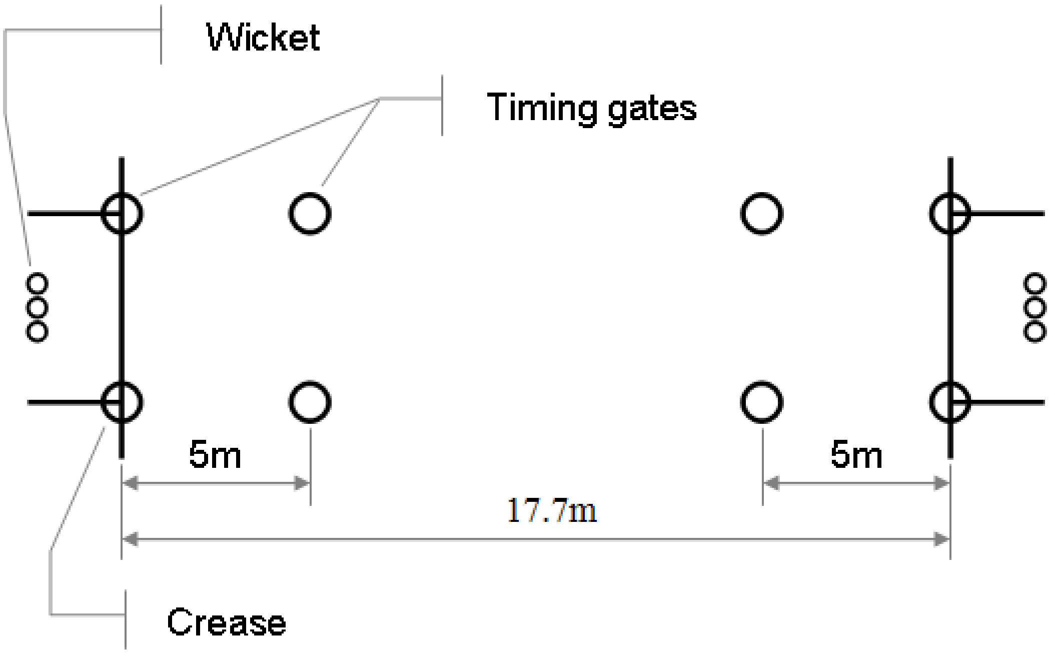


Figure 5. 2: Schematic diagram of running time test set up

Figure 5. 3: Positioning of the 0.9 kg mass for the WC tests

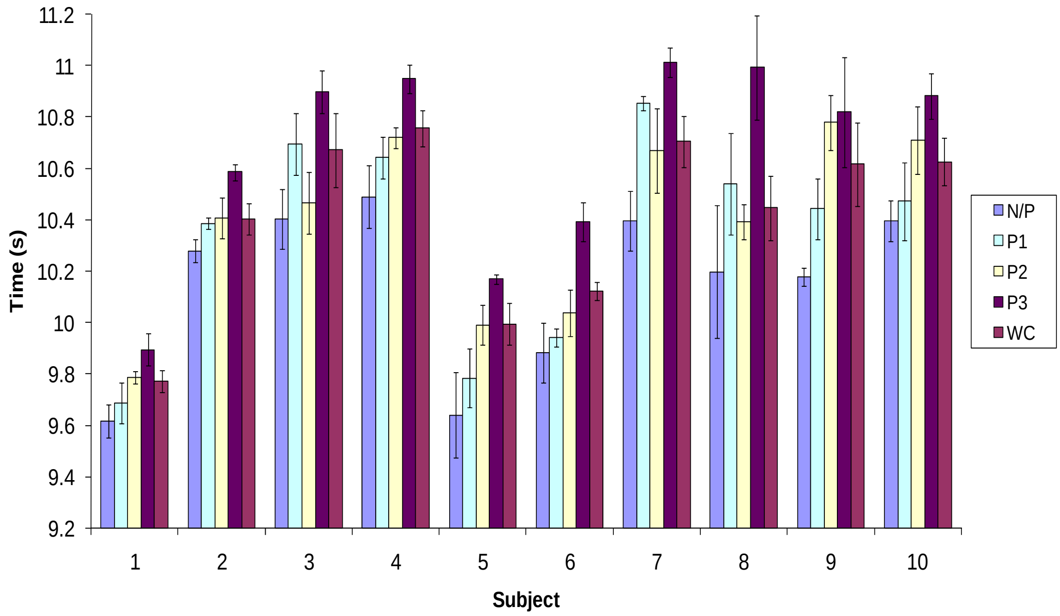


Figure 5. 4:Mean time taken to complete three runs in each condition for all 10 subjects ±1 standard deviation

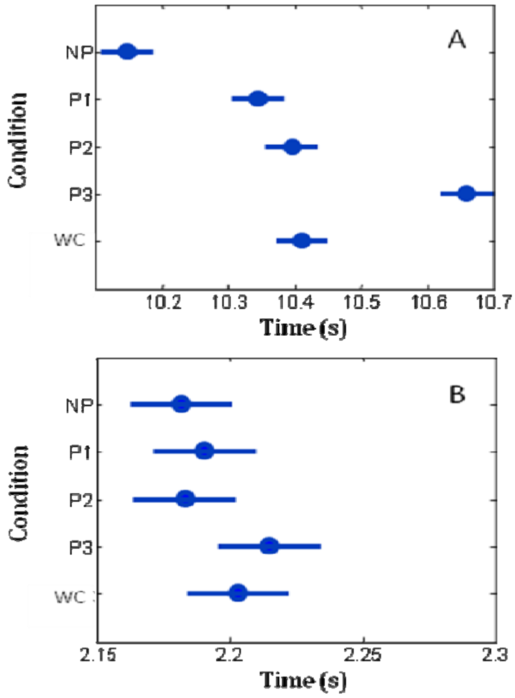


Figure 5. 5: Mean ± one Gabriel comparison interval for A) overall time, B) time taken to turn for the 5 conditions of no pads (NP), weighted comparison (0.9kg), pad type 1 (P1) (0.54kg), pad type 2 (P2) (0.85kg) and pad type 3 (P3) (0.9kg)

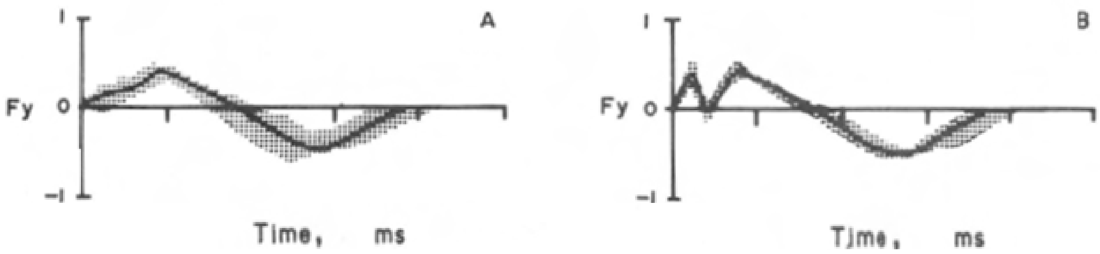


Figure 5. 6: Example of a typical mediolateral GRF trace for a A) Rearfoot and B) Midfoot striker (Cavanagh and Lafortune, 1980)

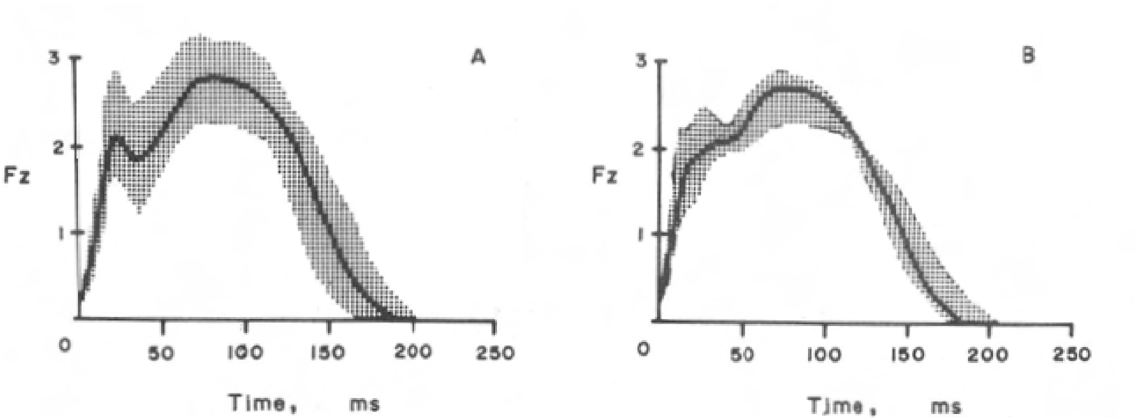


Figure 5. 7: Example of a typical vertical GRF trace for a A) Rearfoot and B) Midfoot striker (Cavanagh and Lafortune, 1980)

Figure 5. 8: Subject 4 completing a running trial in P2

Figure 5. 9: CODA head unit (Codamotion, 2010)

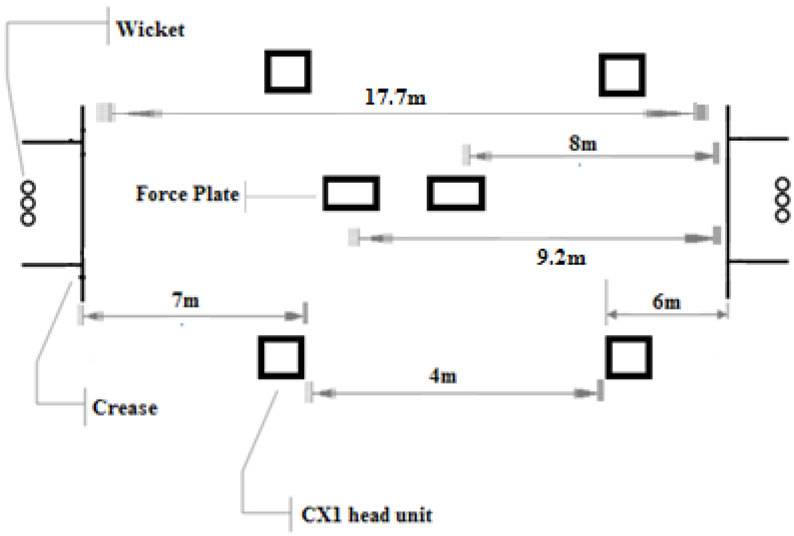


Figure 5. 10: Schematic diagram of running kinematic test set up

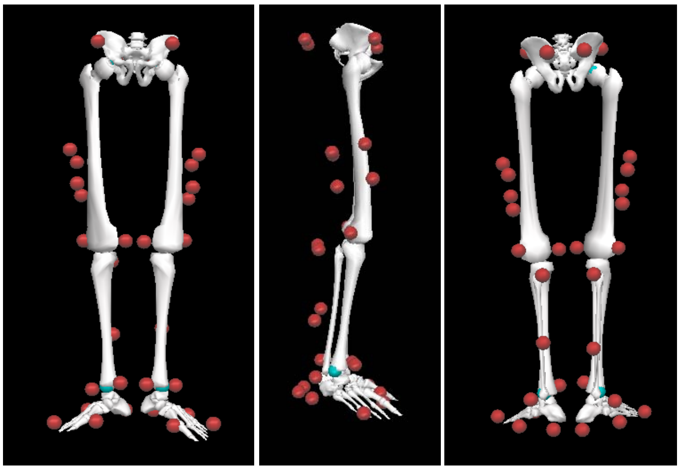


Figure 5. 11: Static capture of full marker set up in visual 3D (version 4)

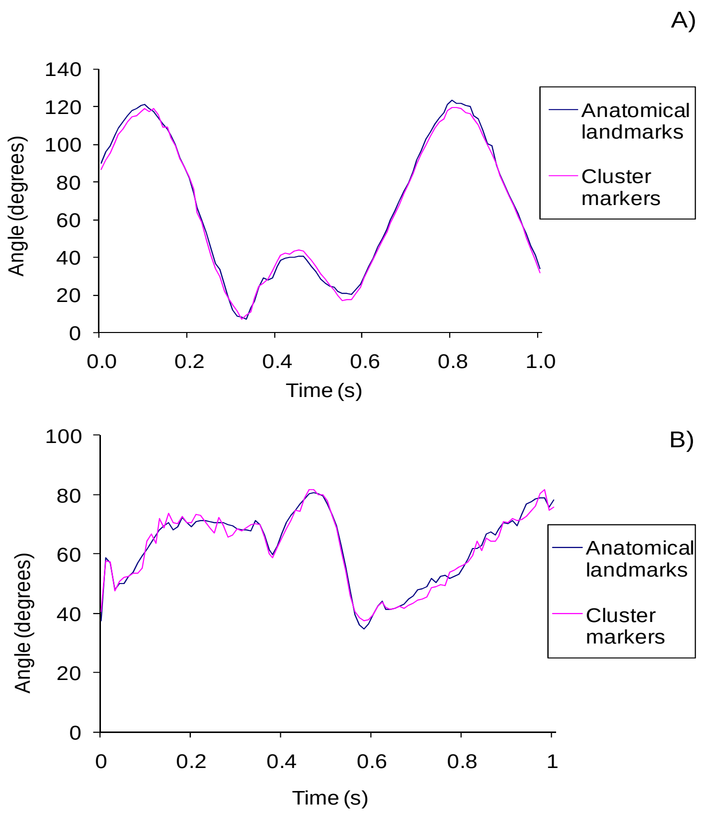


Figure 5. 12: Comparison of A) knee and B) ankle angle for the left leg when running using cluster markers and anatomical landmarks

Figure 5. 13: Pad marker locations

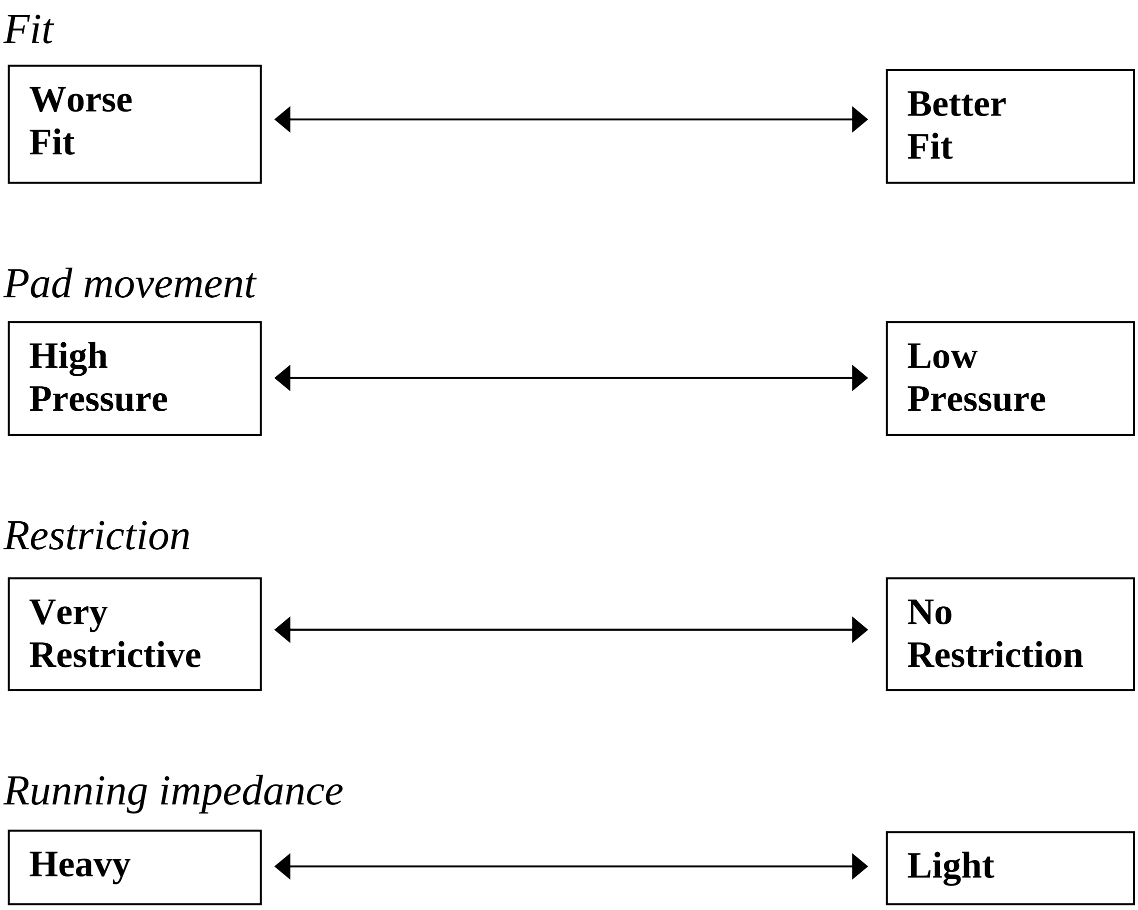


Figure 5. 14: Subject response scales for perceived fit, pad movement, restriction and running impedance

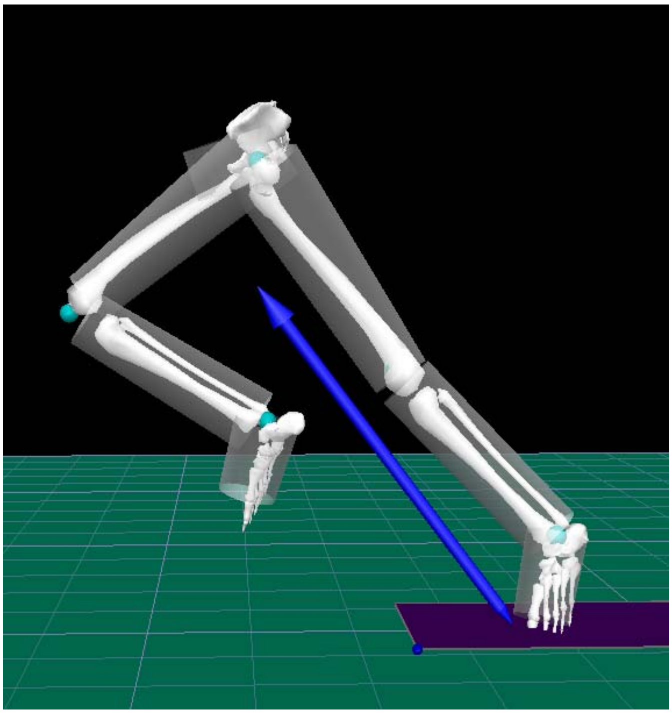


Figure 5. 15: 3D kinematic model with force vector

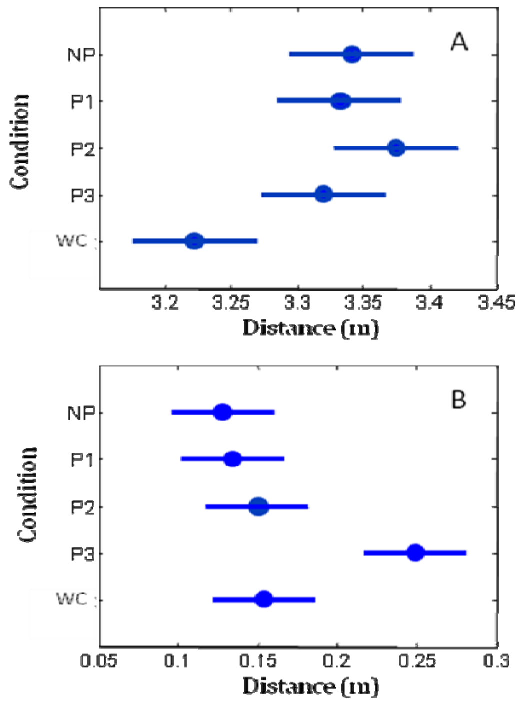


Figure 5. 16: Mean ± one Gabriel comparison interval for A) stride length and B) stride width for all five conditions, with a significant difference demonstrated when the Gabriel comparison intervals do not overlap

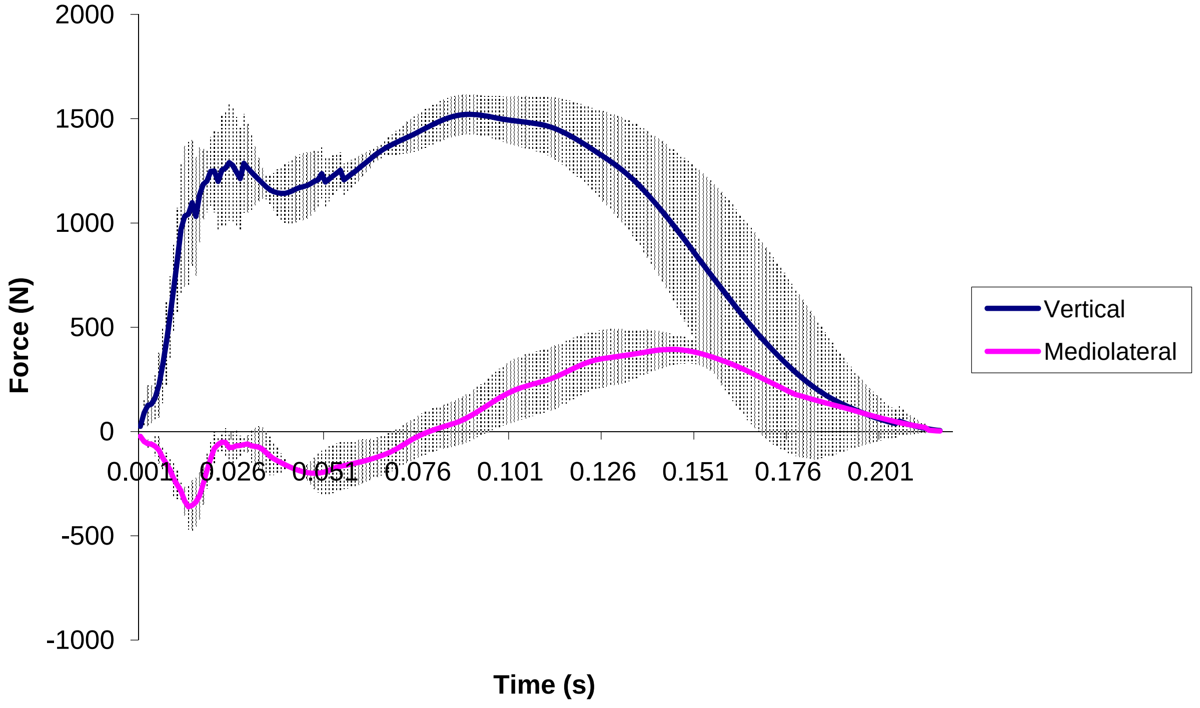


Figure 5. 17: Mediolateral and vertical GRF trace for Subject 2 in the N/P condition ±1 standard deviation

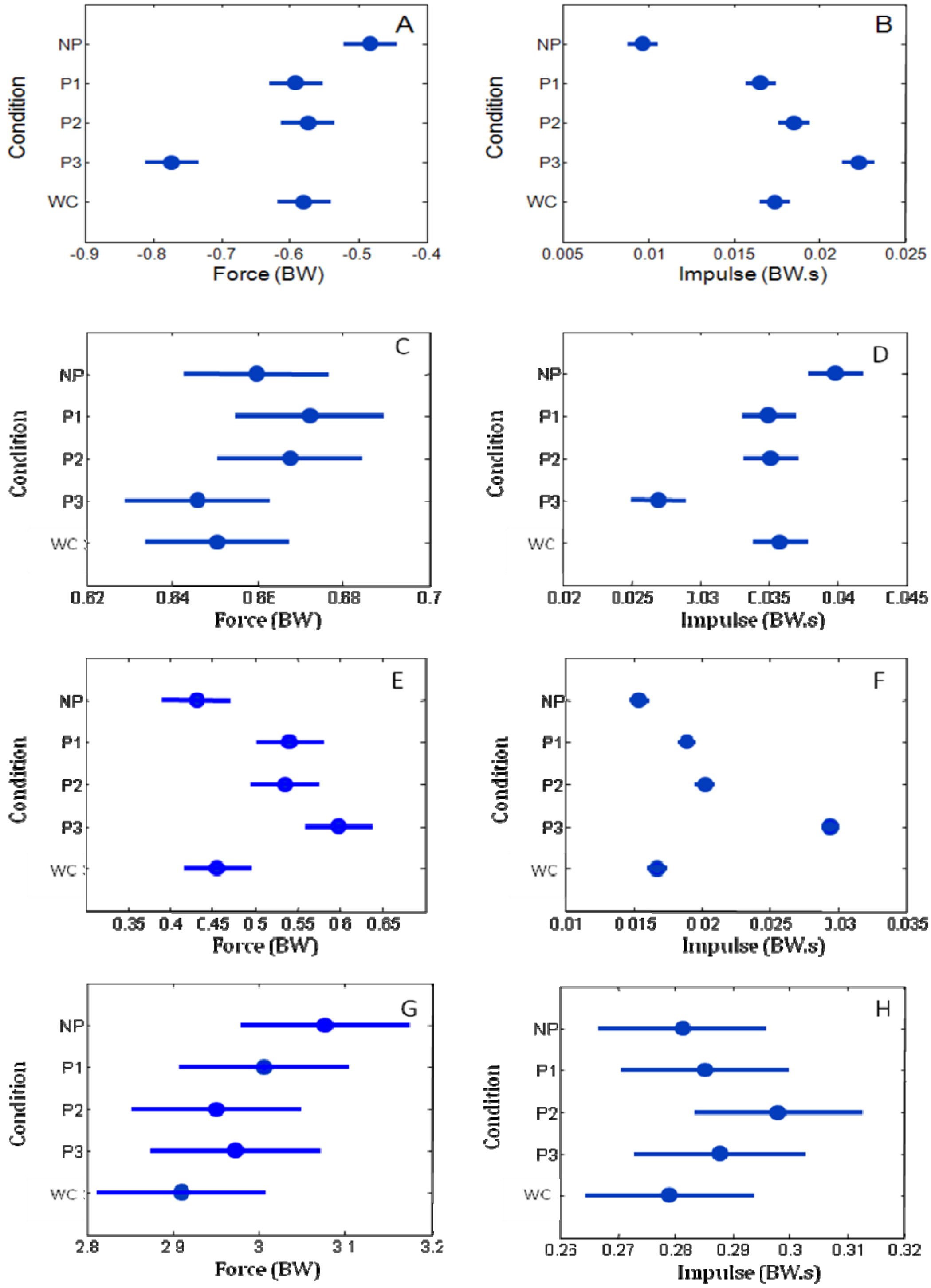


Figure 5. 18: Mean GRF ± one Gabriel comparison interval for all conditions in regards to A) Maximum braking force, B) Braking impulse, C) Maximum propulsive force, D) Propulsive impulse, E) Maximum medial lateral force, F) Medial lateral impulse, G) Maximum vertical force and H) Vertical impulse, with significant differences demonstrated when the Gabriel confidence intervals do not overlap

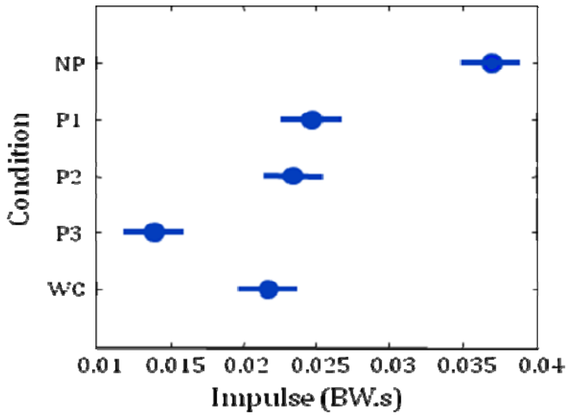
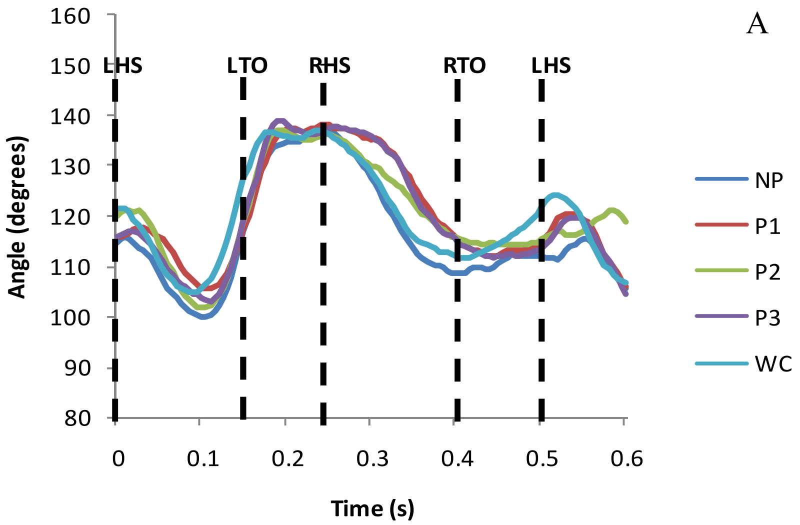


Figure 5. 19: Mean anterior/posterior impulse ± one Gabriel confidence interval, with a significant difference demonstrated when the Gabriel comparison intervals do not overlap



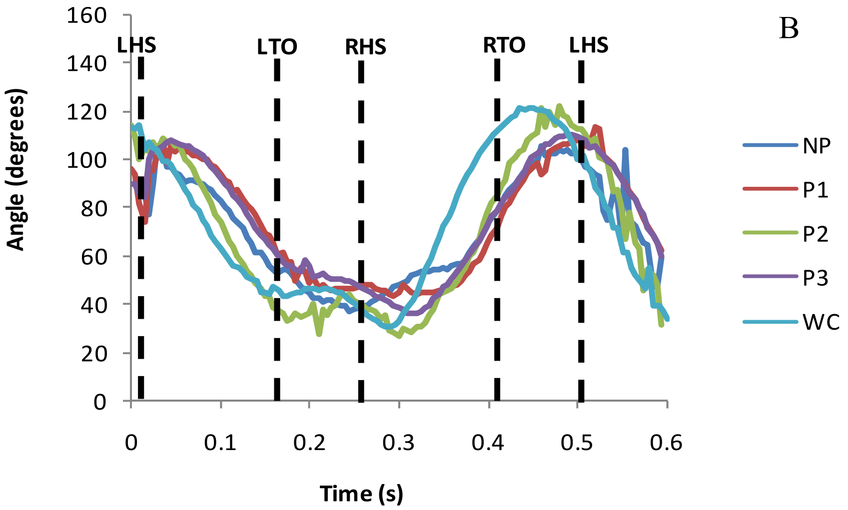


Figure 5. 20: Mean joint kinematics for Subject 3 for one complete stride with event labels (left heel strike (LHS), left toe off (LTO), right heel strike (RHS) and right toe off (RTO)) for A) left knee angle and B) left ankle angle for all five conditions

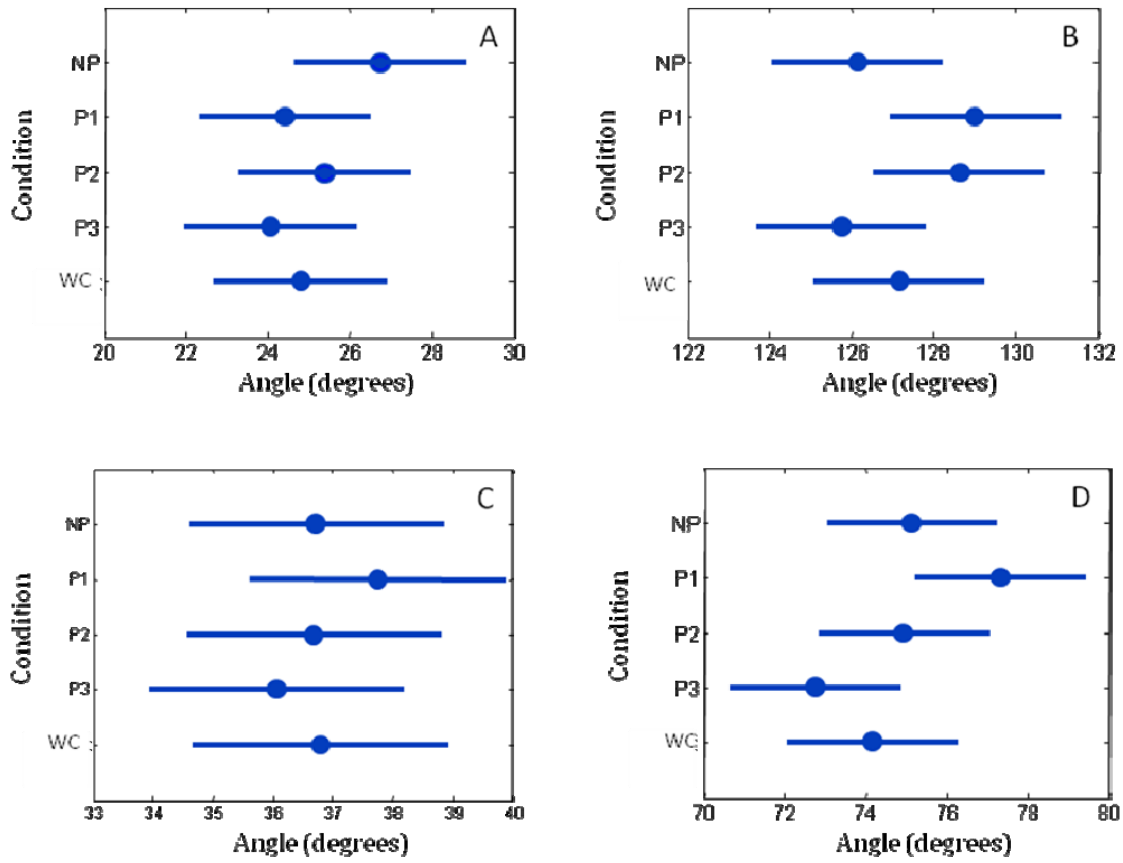


Figure 5. 21: Mean ± one Gabriel comparison interval for A) Maximum knee extension, B) Maximum knee flexion, C) Maximum ankle extension and D) Maximum ankle flexion for the left leg, with a significant difference demonstrated when the Gabriel comparison intervals do not overlap

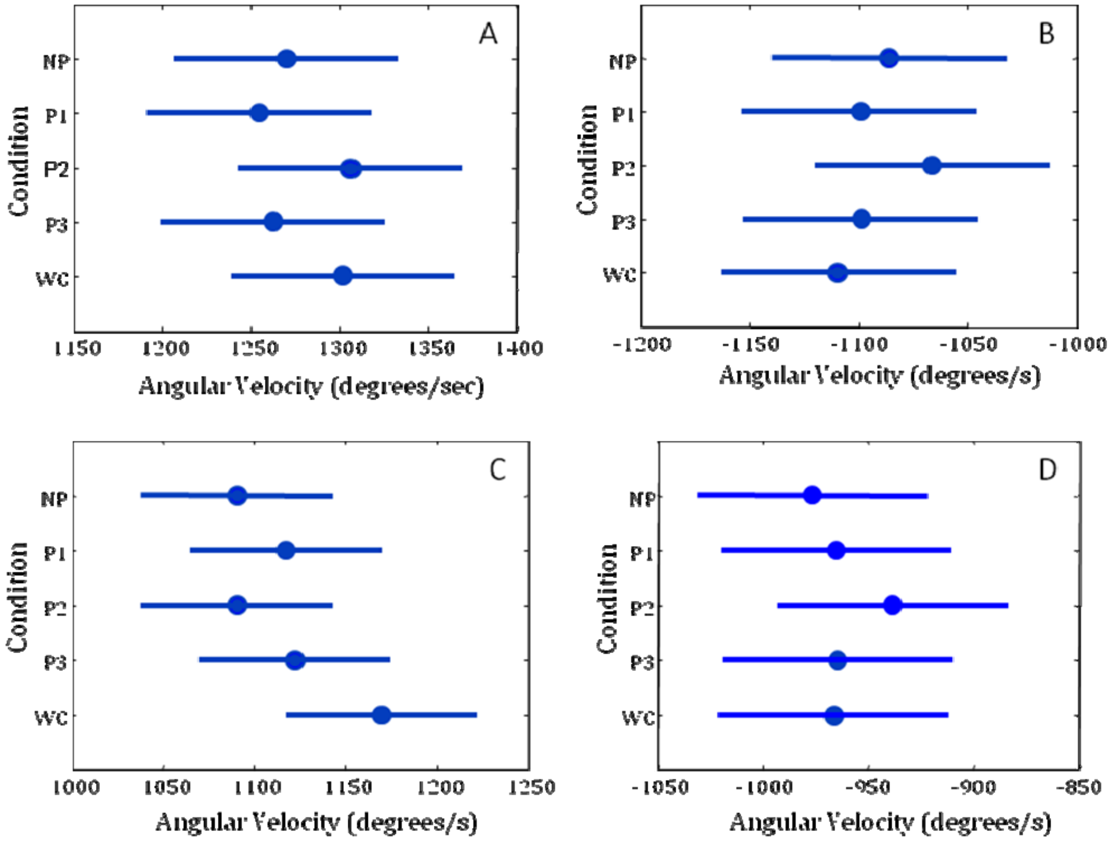


Figure 5. 22: Mean ± one Gabriel comparison interval for A) Maximum knee extension angular velocity and B) Maximum knee flexion angular velocity, C) Maximum ankle extension angular velocity and D) Maximum ankle flexion angular velocity for the left leg, with a significant difference demonstrated when the Gabriel confidence intervals do not overlap

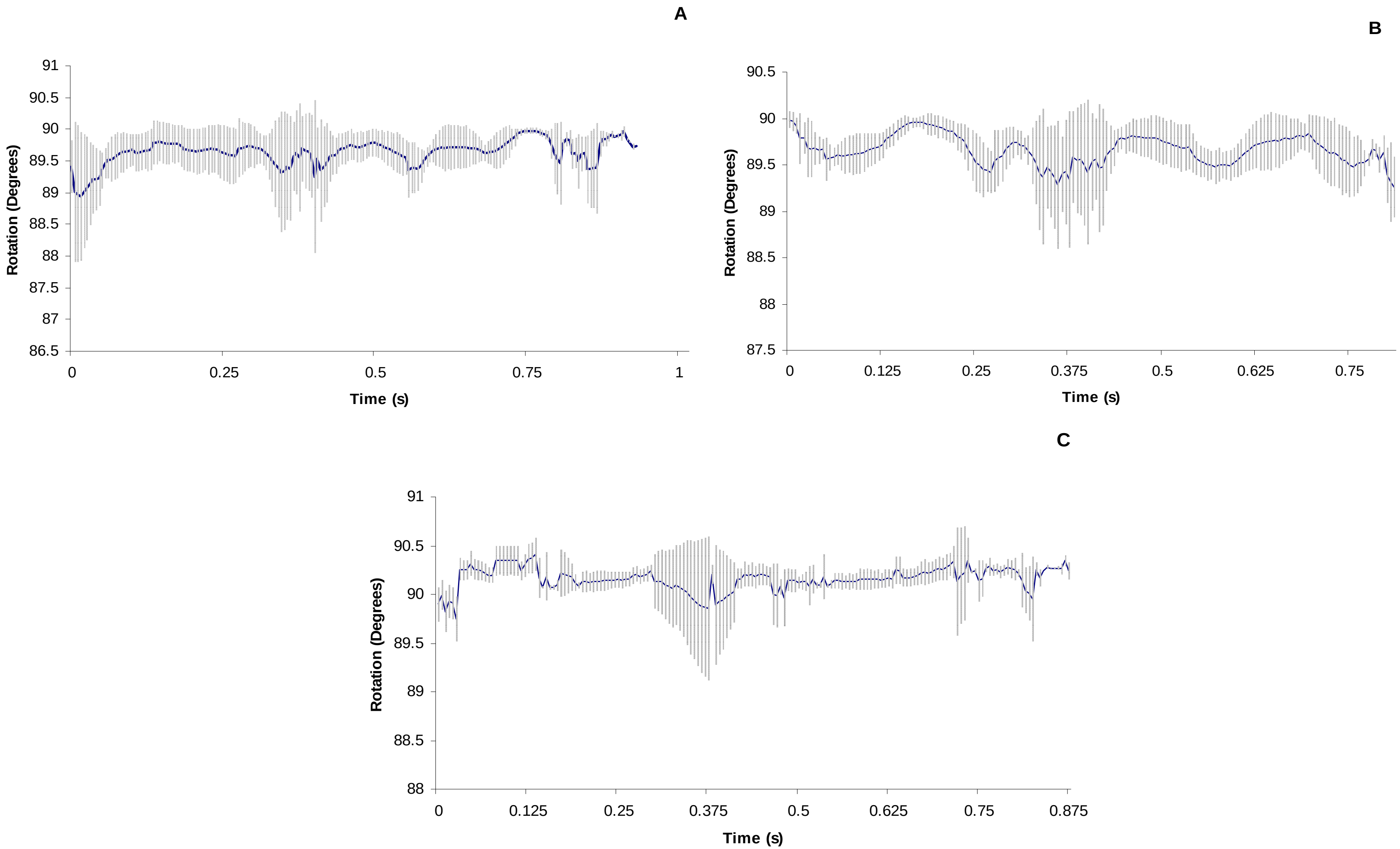


Figure 5. 23: Mean pad rotation (±1 standard deviation) about the front leg for A) P1, B) P2 and C) P3

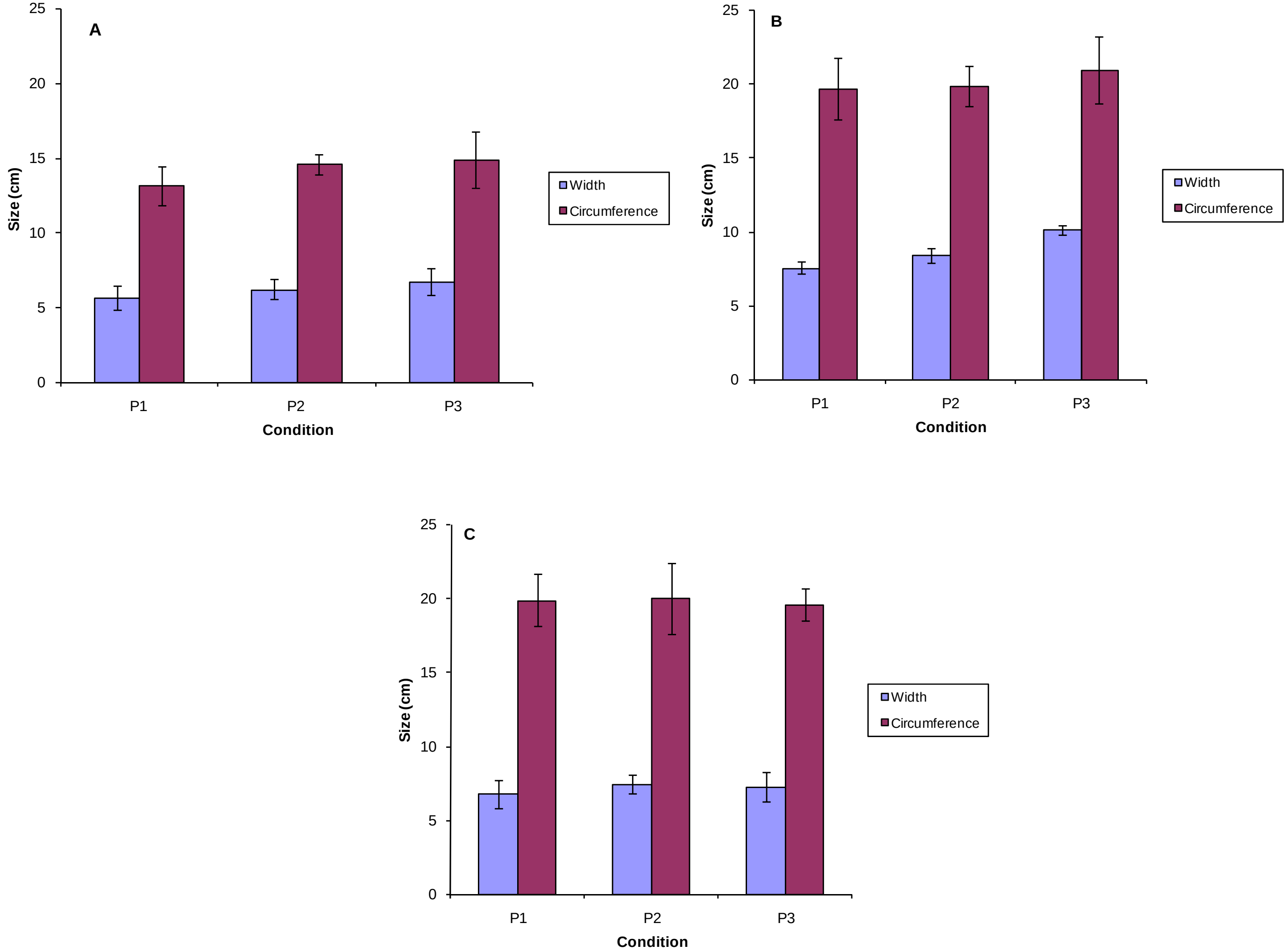


Figure 5. 24:Mean additional leg width and circumference from wearing cricket pads at A)the thigh, B) the knee and C) the calf ±1 standard deviation

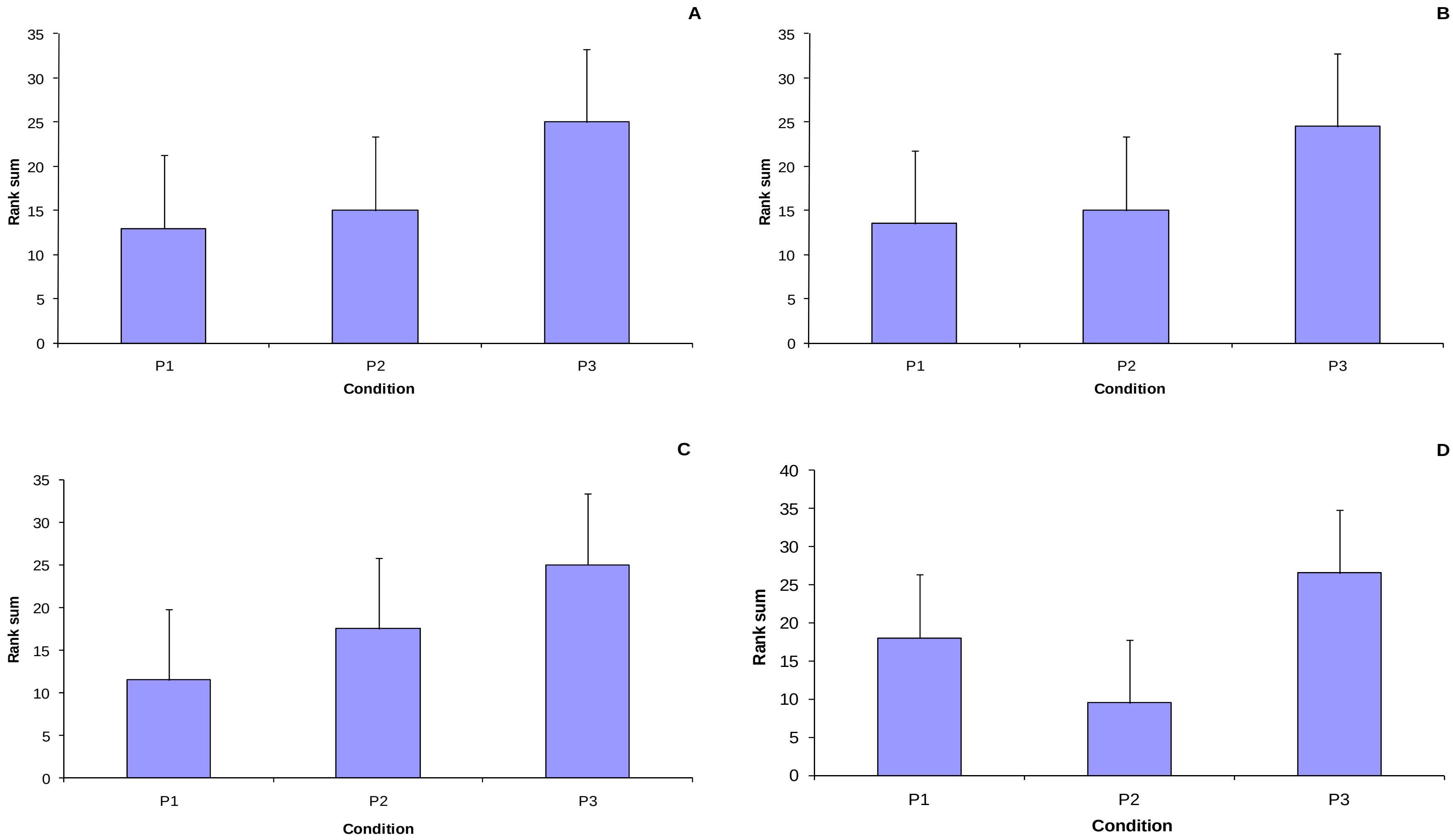


Figure 5. 25: Subjective rankings of the three pads in terms of perceived A) Fit, B) Restriction, C) Pad movement and D) Running impedance +1 LSD_{rank}

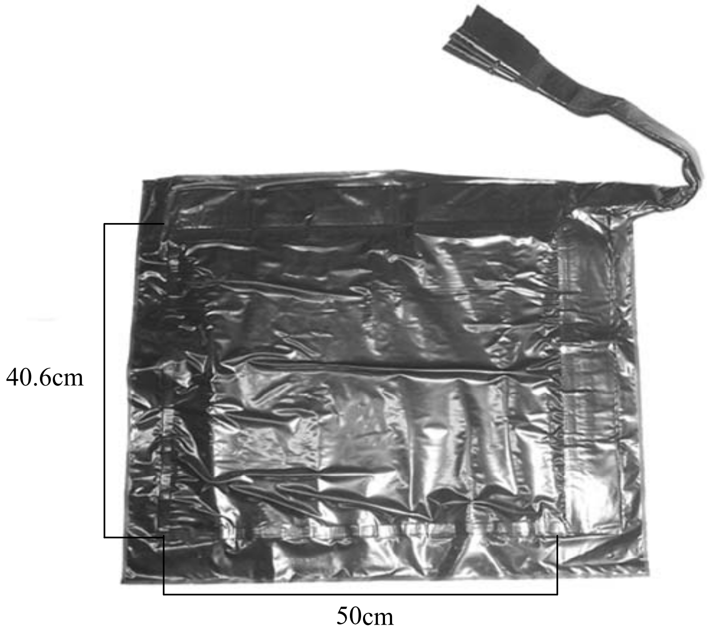


Figure 6. 1: X-sensor LX200 custom sensor

Figure 6. 2: Photron fastcam high speed camera (Photron, 2010)

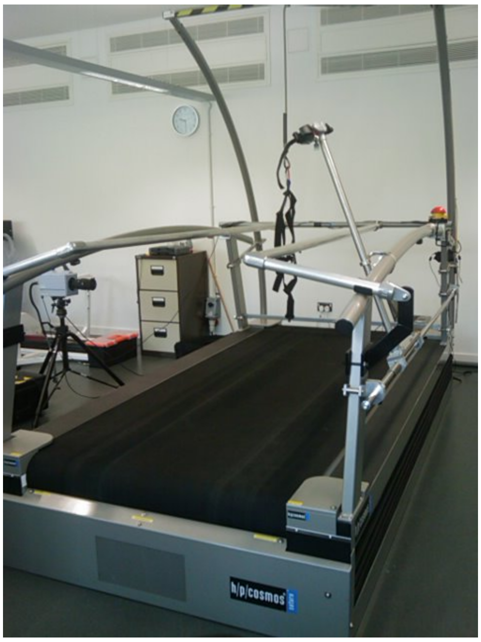


Figure 6. 3: HP Cosmos Saturn treadmill

Figure 6. 4: Sensor mat mounted beneath pad on leading leg of cricketer

Pad Width:

☐Much too Narrow ☐Too Narrow ☐Ideal ☐Too wide ☐Much too wide

Pad Length:

☐Much too short ☐Too short ☐Ideal ☐Too long ☐Much too long

Figure 6. 5: Subjective rating scale used within the final assessment of each pad, assessing pad width and length

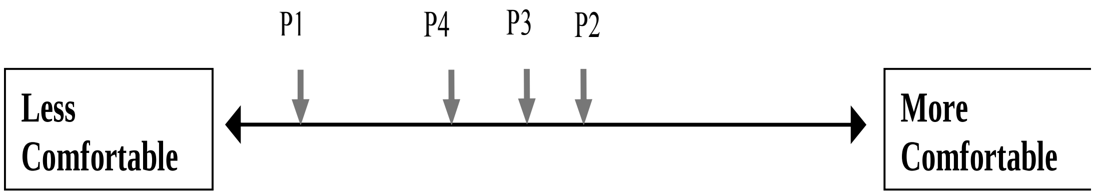


Figure 6. 6: Example of the rating scale used to subjectively rank the pads post use

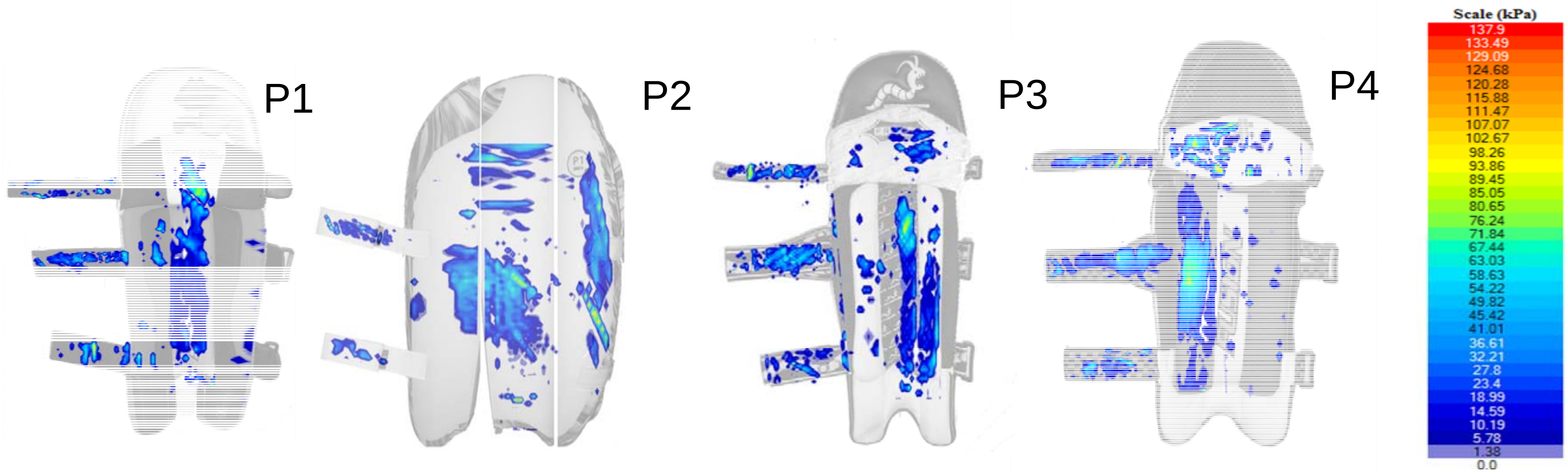


Figure 6. 7: Subject 5's X-sensor pressure maps for the static measurement for P1, P2, P3 and P4

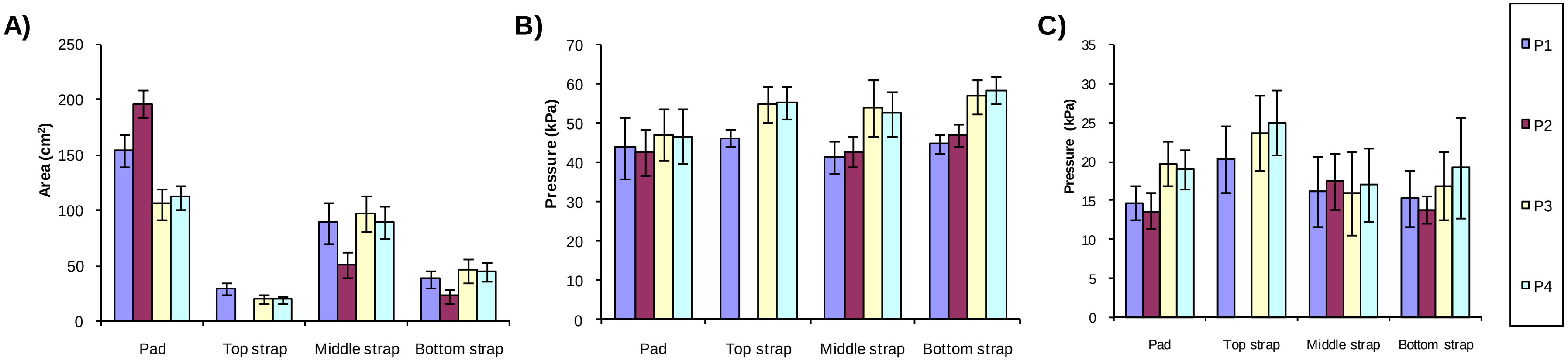


Figure 6. 8: Numerical compilation of nine subject's static measurement results for A) contact area, B) peak pressure and C) average pressure

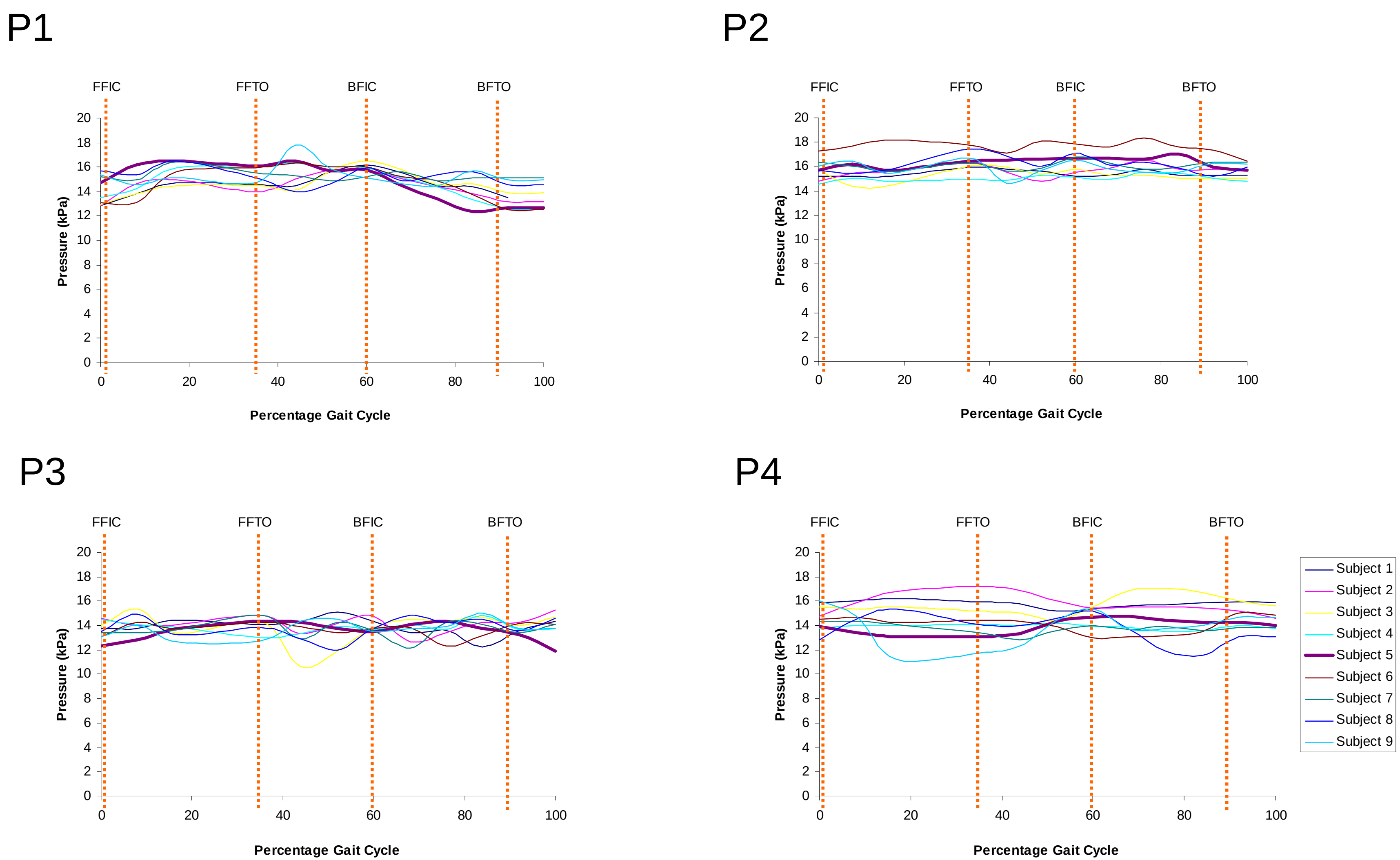


Figure 6. 9: Mean pad average pressure for each subject for P1, P2, P3 and P4

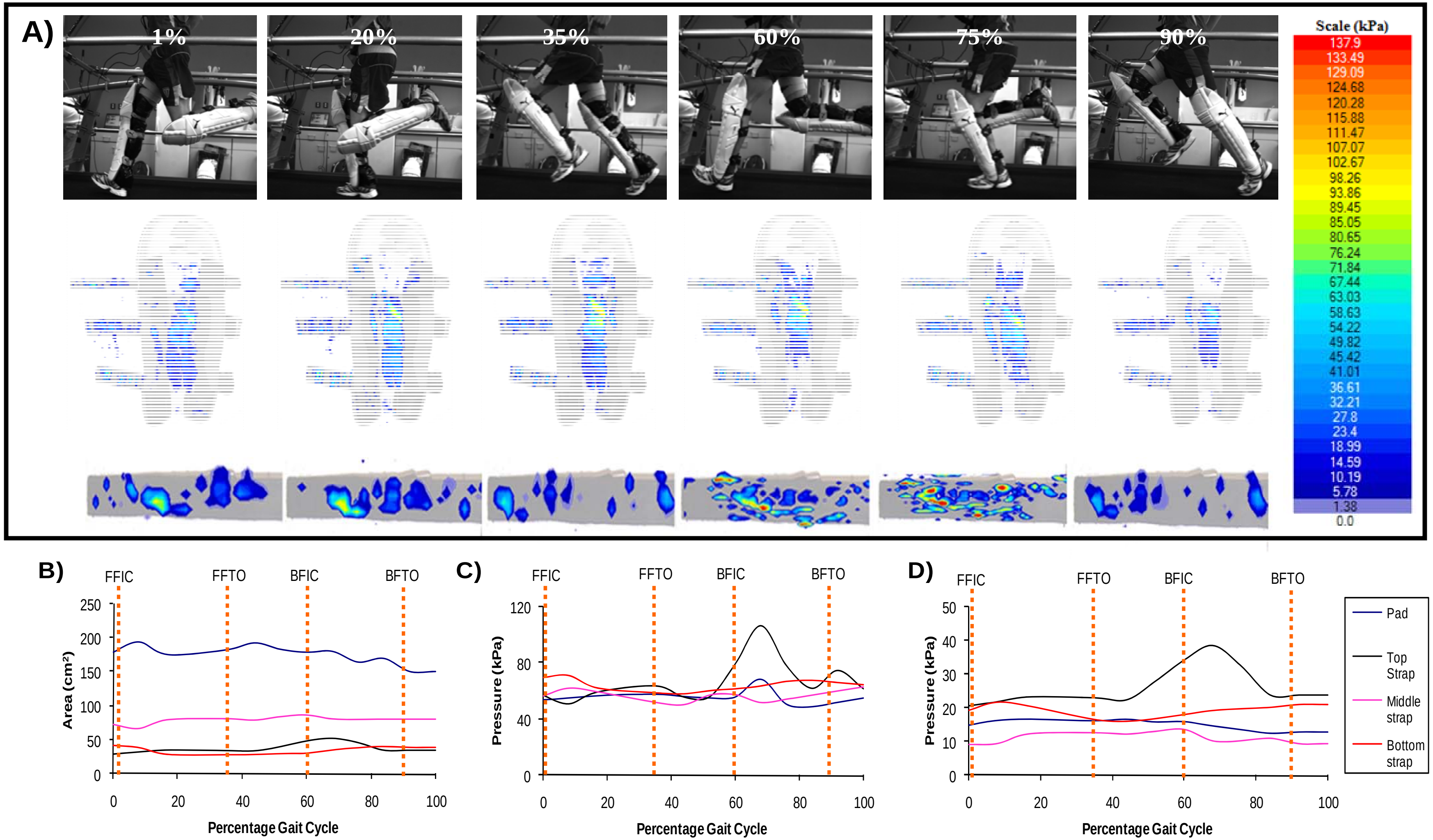


Figure 6. 10: A compilation of data for Subject 5 wearing P1 A) Pressure maps during one complete stride, with magnified views of the top strap, B) mean contact area, C) mean peak pressure and D) mean average pressure for each of the four regions for all 20 strides

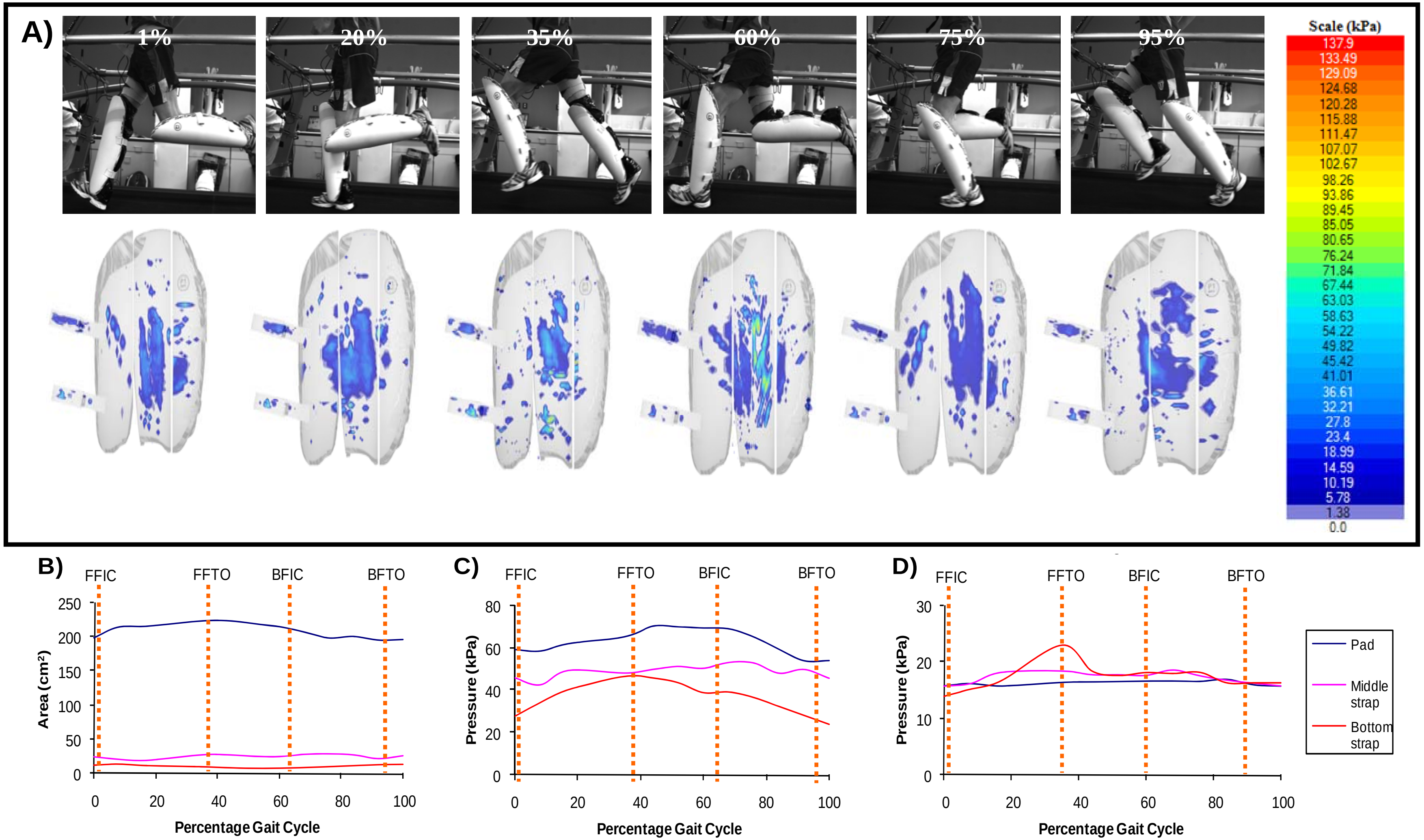


Figure 6. 11: A compilation of data for Subject 5 wearing P2 A) Pressure maps during one complete stride, B) mean contact area, C) mean peak pressure and D) mean average pressure for each of the four regions for all 20 strides

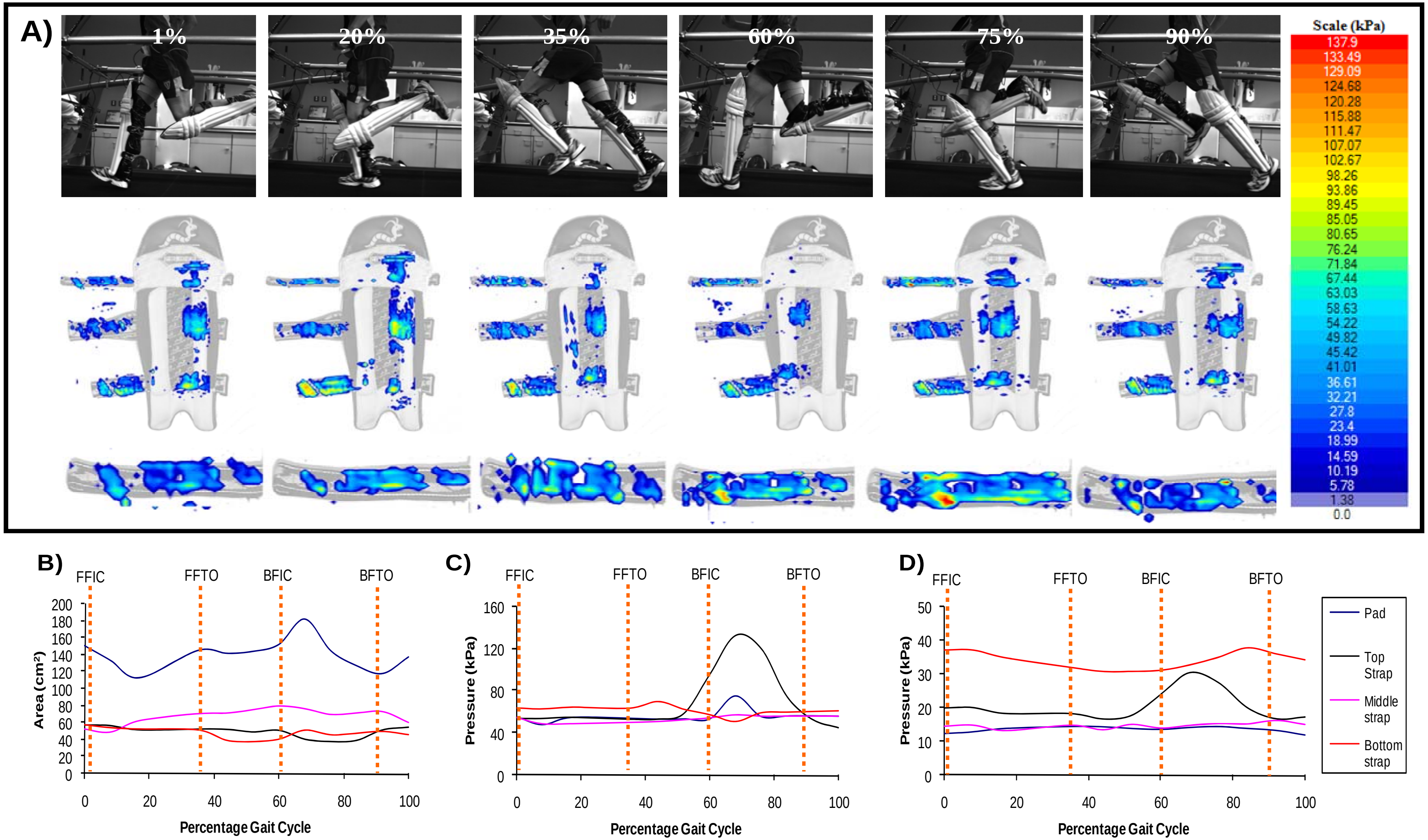


Figure 6. 12: A compilation of data for Subject 5 wearing P3 A) Pressure maps during one complete stride, with magnified views of the top strap, B) mean contact area, C) mean peak pressure and D) mean average pressure for each of the four regions for all 20 strides

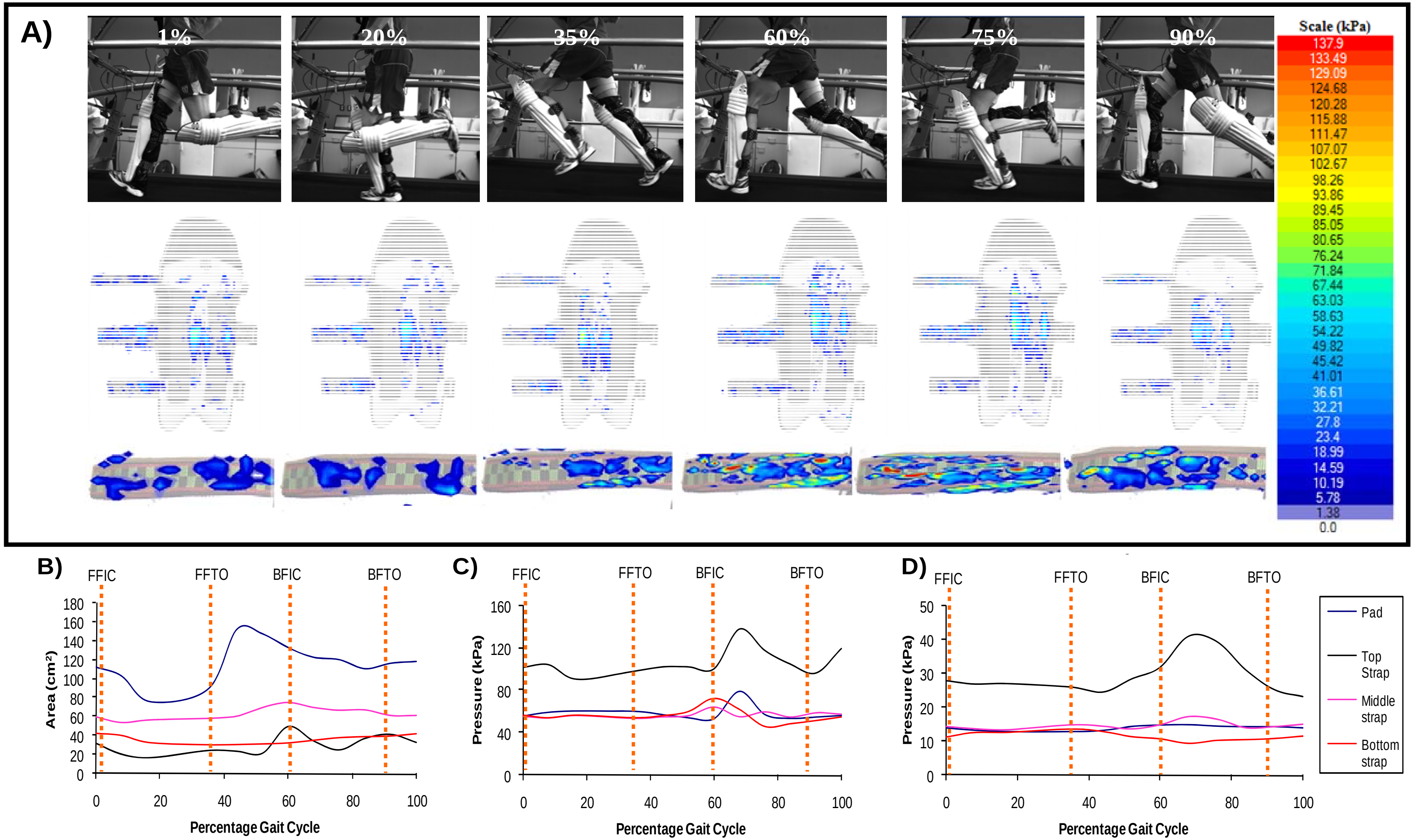


Figure 6. 13: A compilation of data for Subject 5 wearing P4 A) Pressure maps during one complete stride, with magnified views of the top strap, B) mean contact area, C) mean peak pressure and D) mean average pressure for each of the four regions for all 20 strides

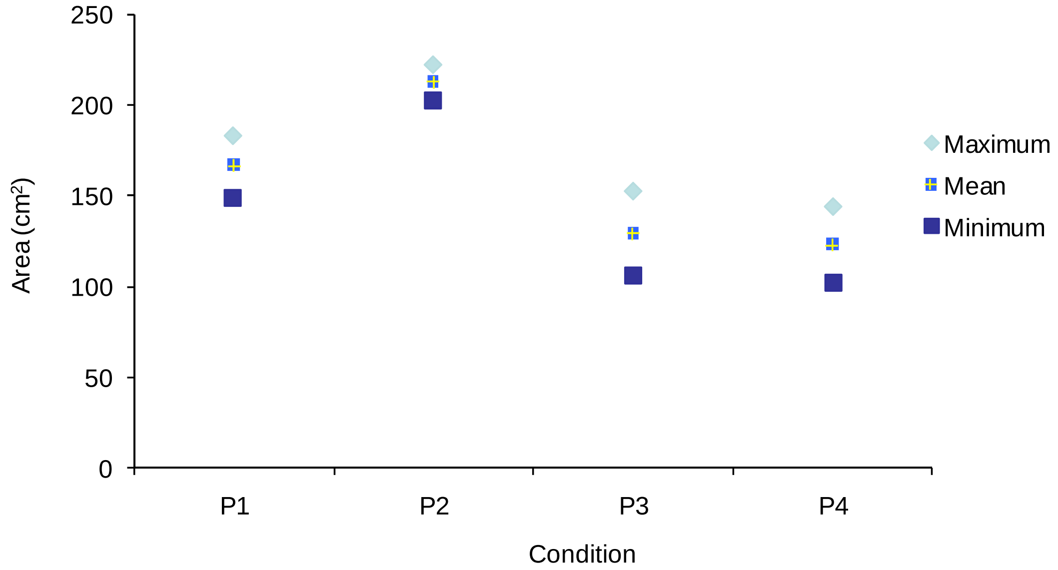


Figure 6. 14: Variation in contact area showing the mean maximum, mean average and mean minimum contact area for all subjects

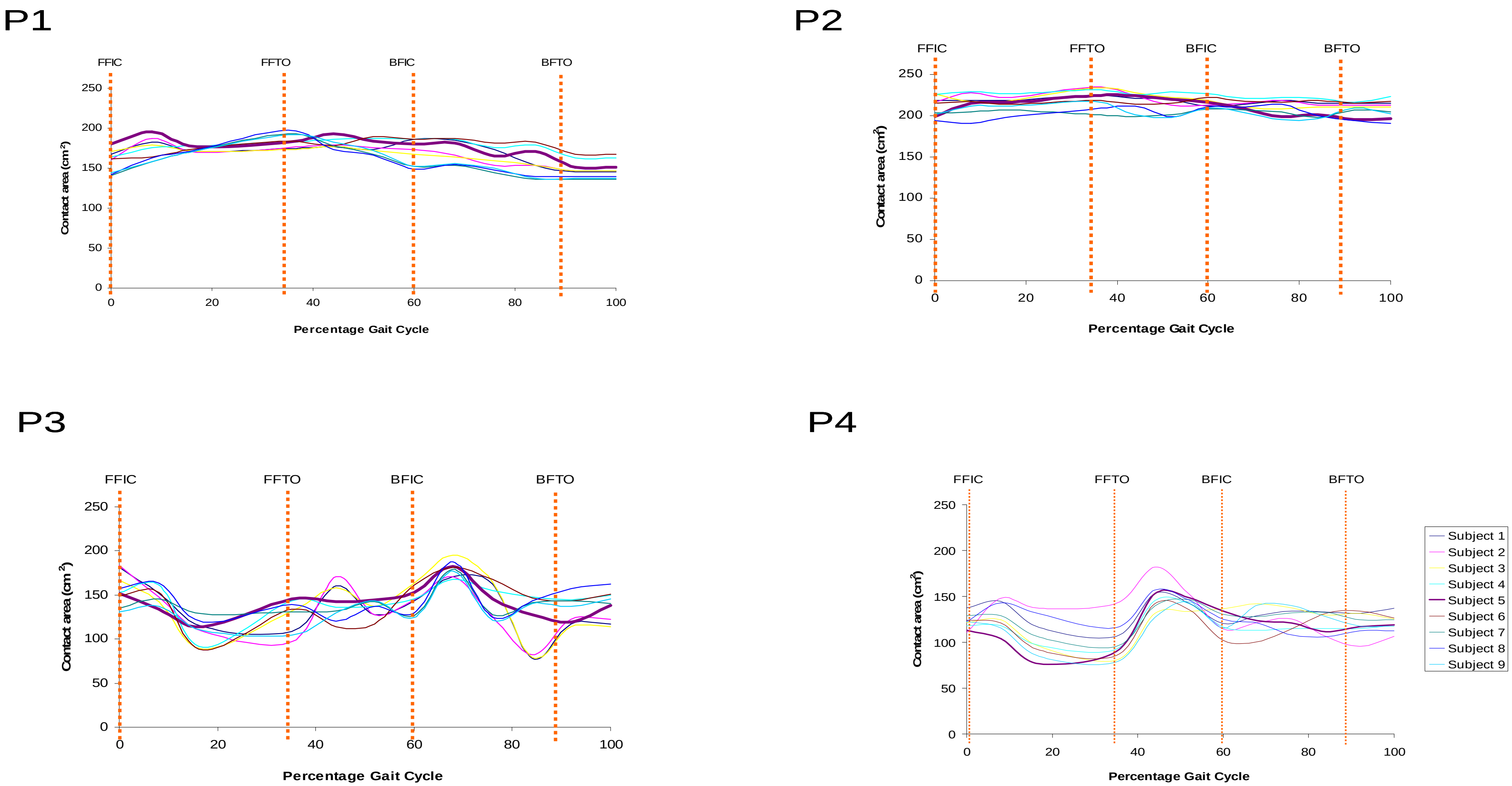


Figure 6. 15: Mean pad contact area for each subject for P1, P2, P3 and P4 over one stride

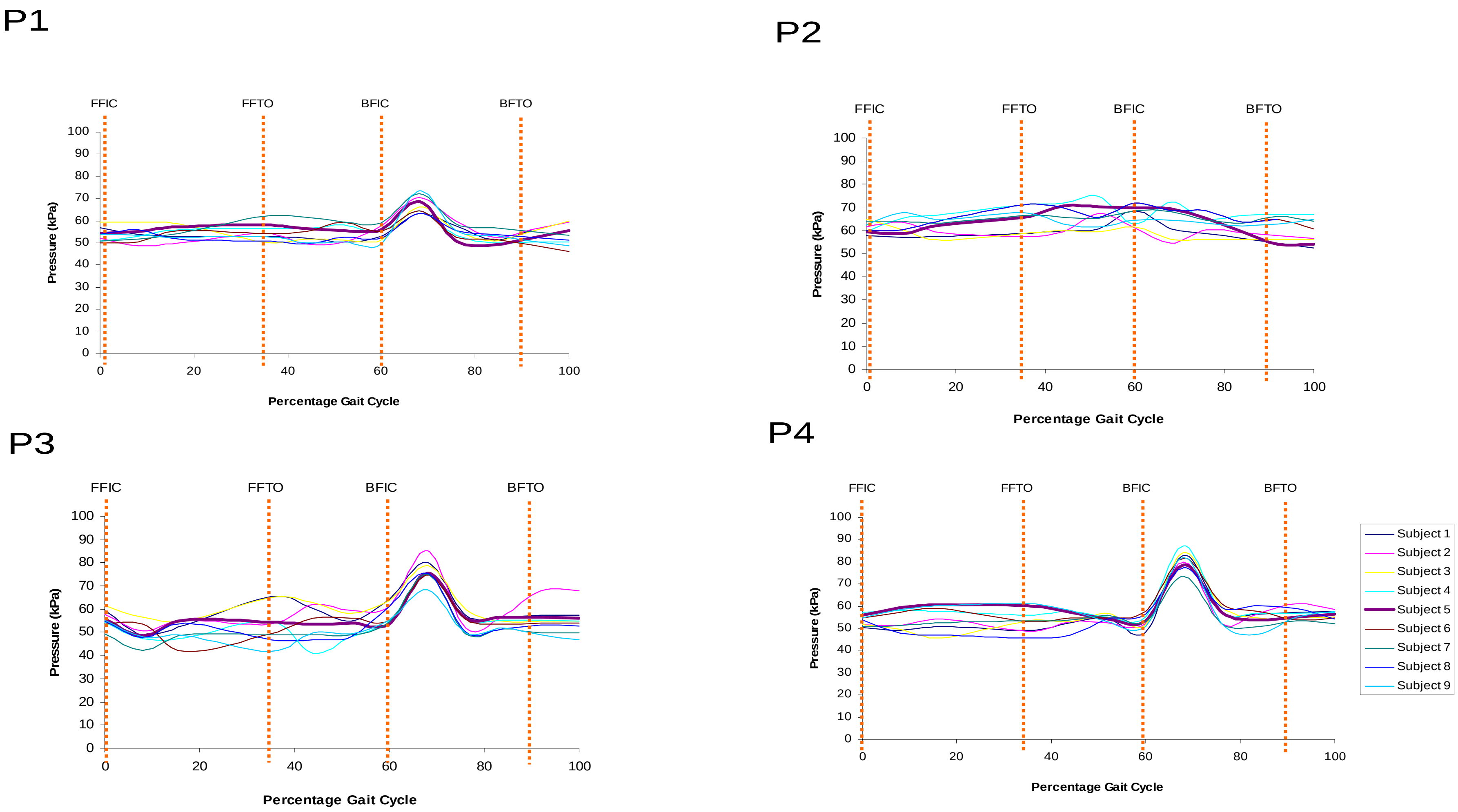


Figure 6. 16: Mean peak pressure for each subject under padded area of P1, P2, P3 and P4 over 1 stride

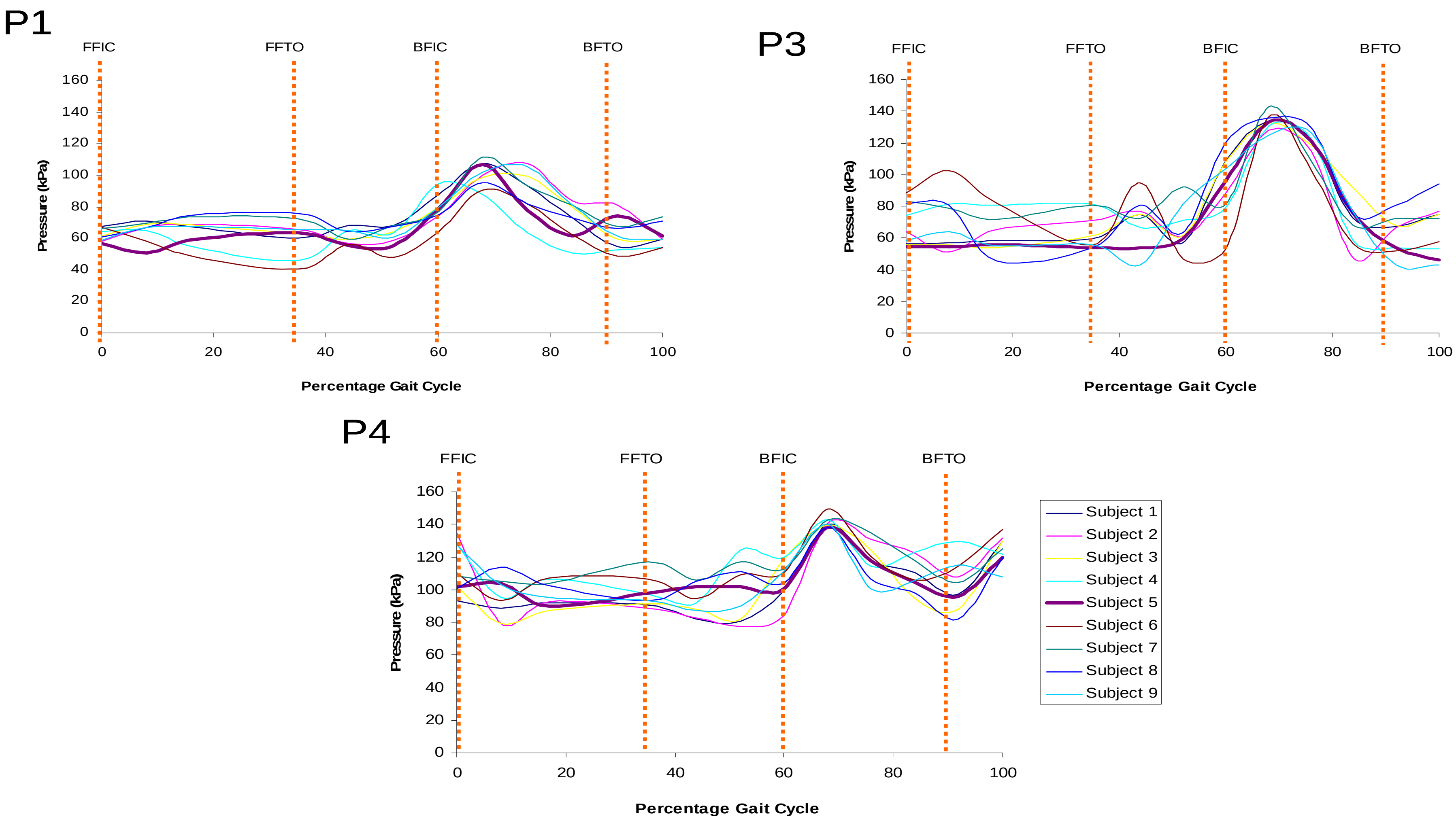


Figure 6. 17: Mean peak pressure for each subject for the top strap of P1, P3 and P4

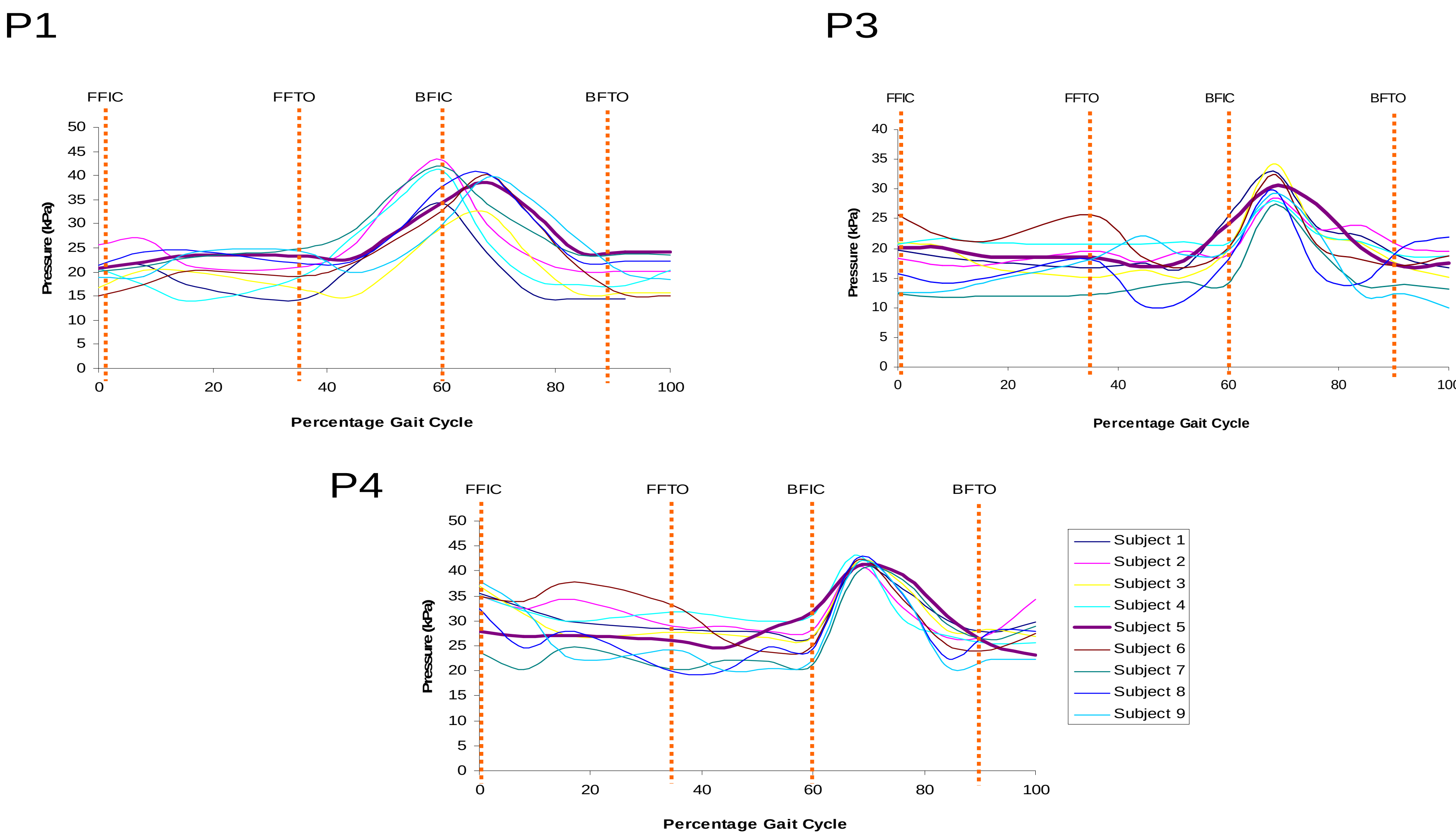


Figure 6. 18: Mean average pressure for each subject for top strap of P1, P3 and P4

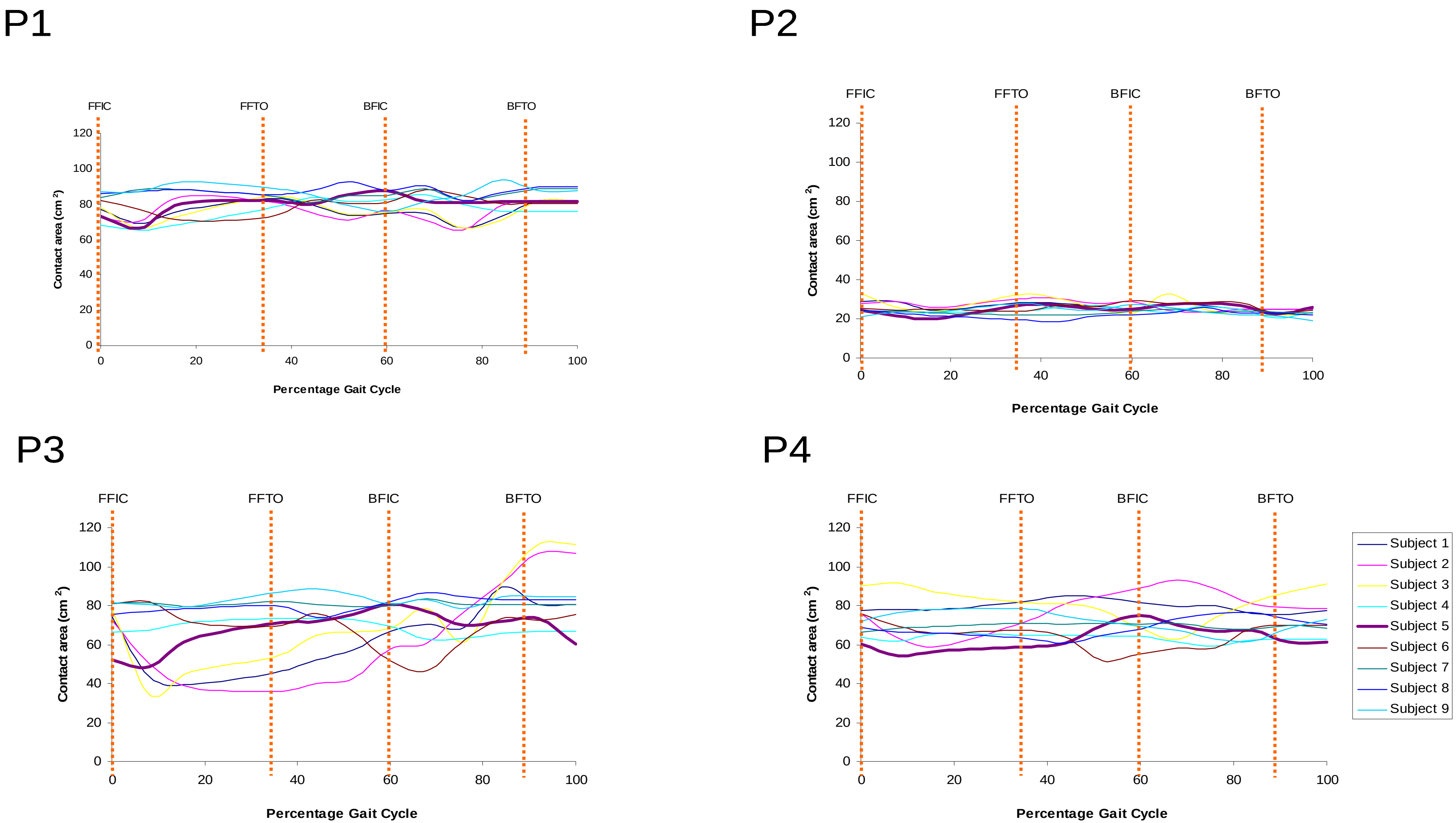


Figure 6. 19: Mean contact area for each subject for middle strap of P1, P2, P3 and P4

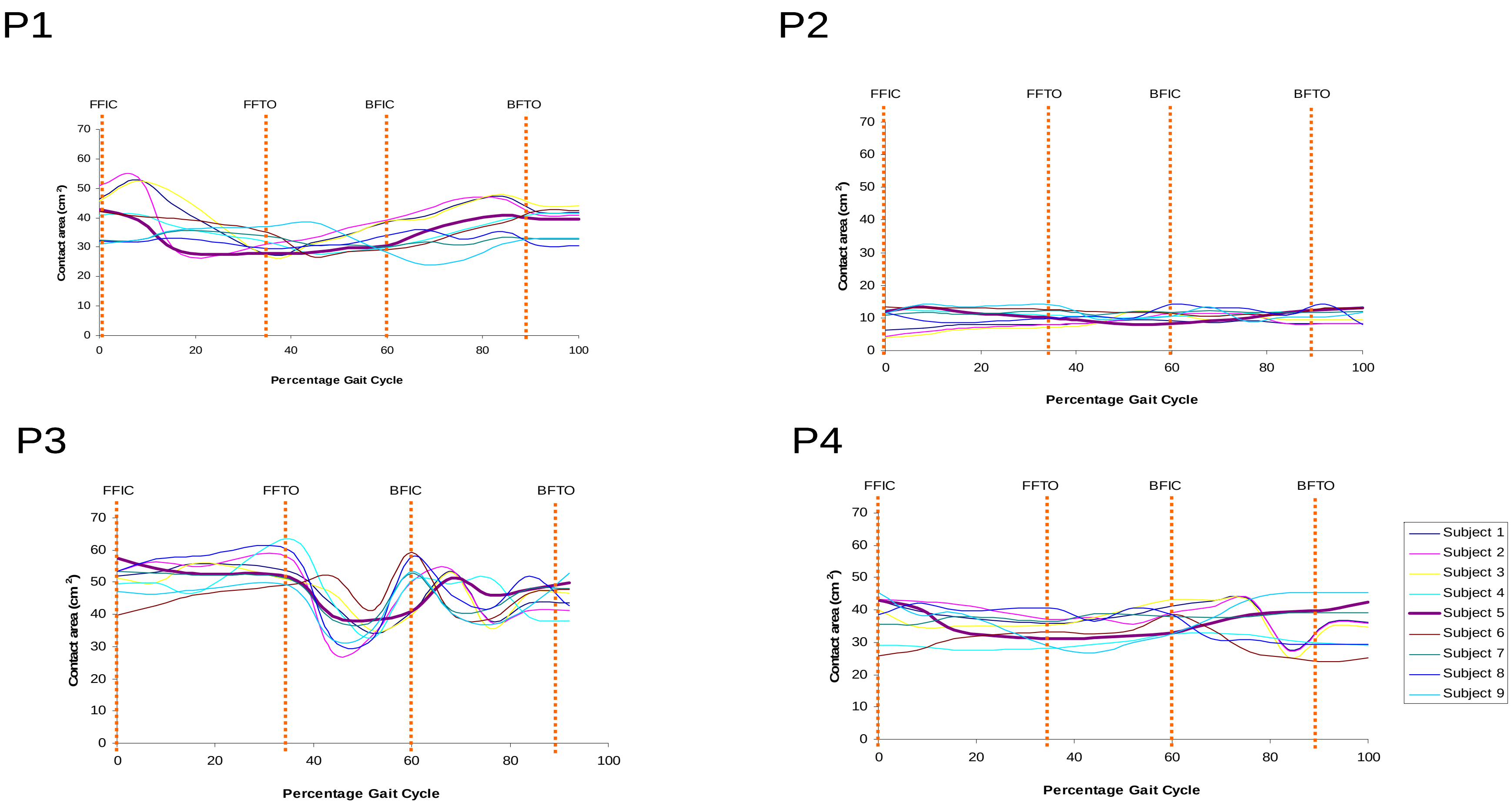


Figure 6. 20: Mean contact area for each subject for bottom strap of P1, P2, P3 and P4

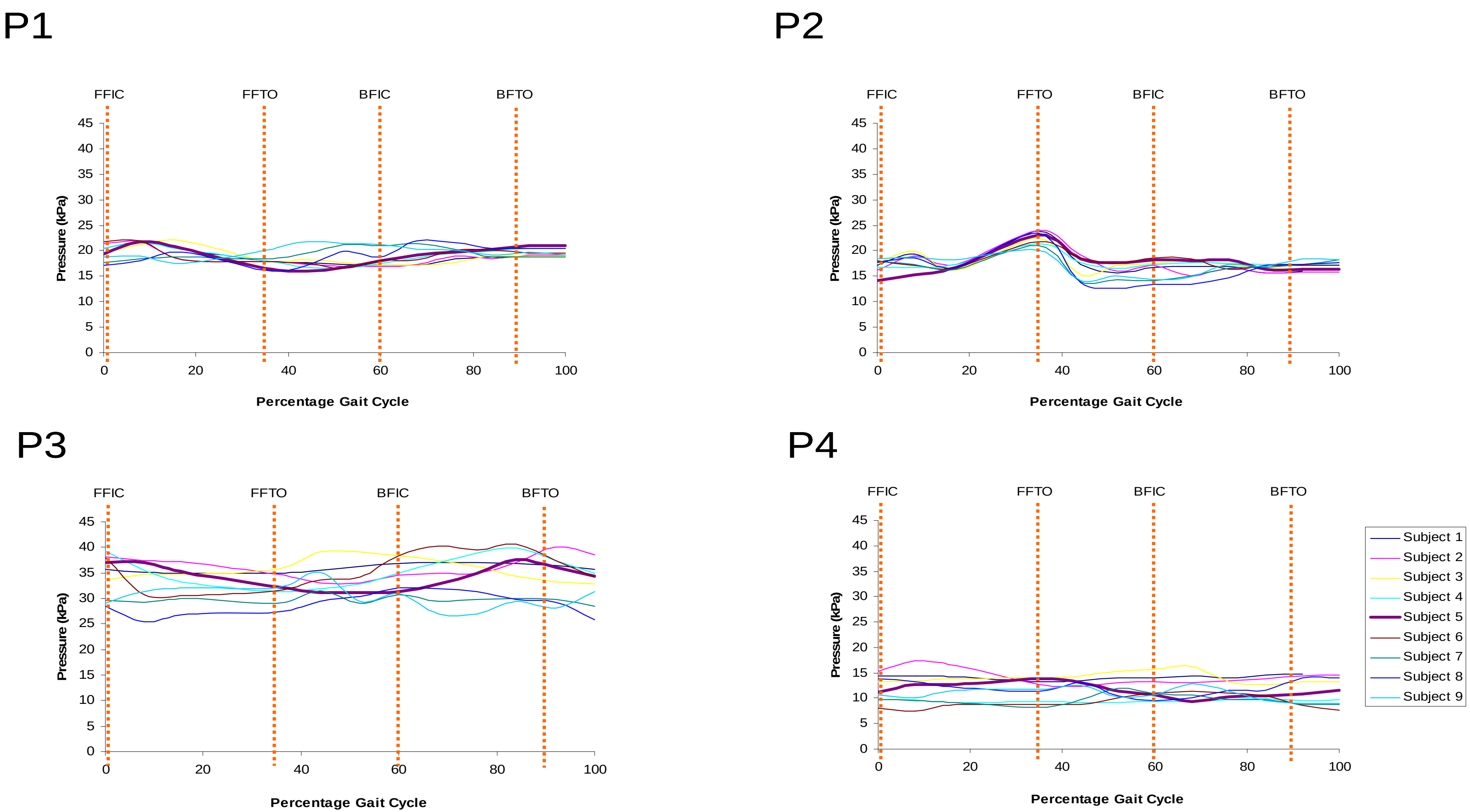


Figure 6. 21: Mean bottom strap average pressure for each subject of P1, P2, P3 and P4

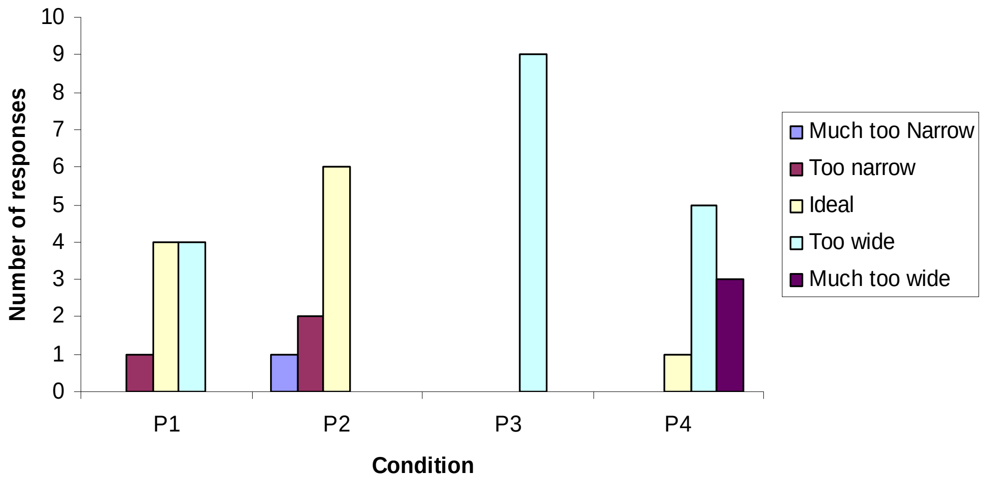


Figure 6. 22: Subjective responses regarding perceived pad width for all padded conditions

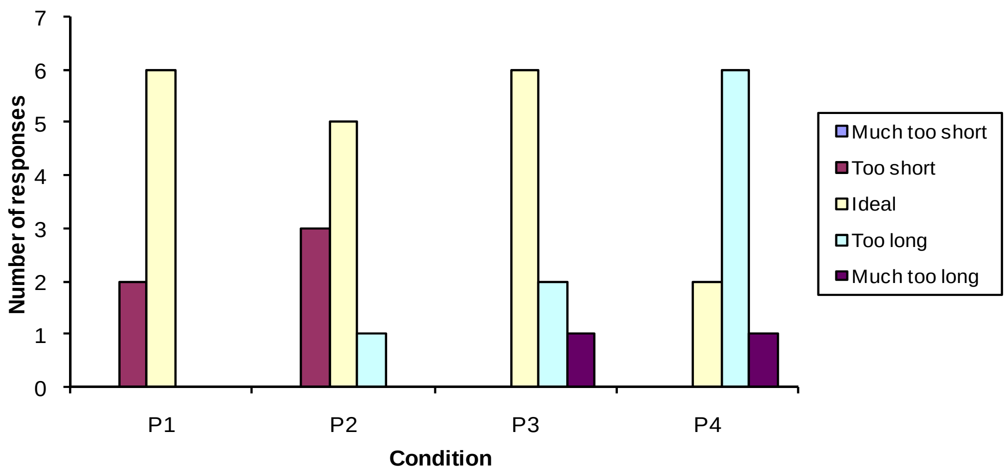


Figure 6. 23: Subjective responses regarding perceived pad length for all padded conditions

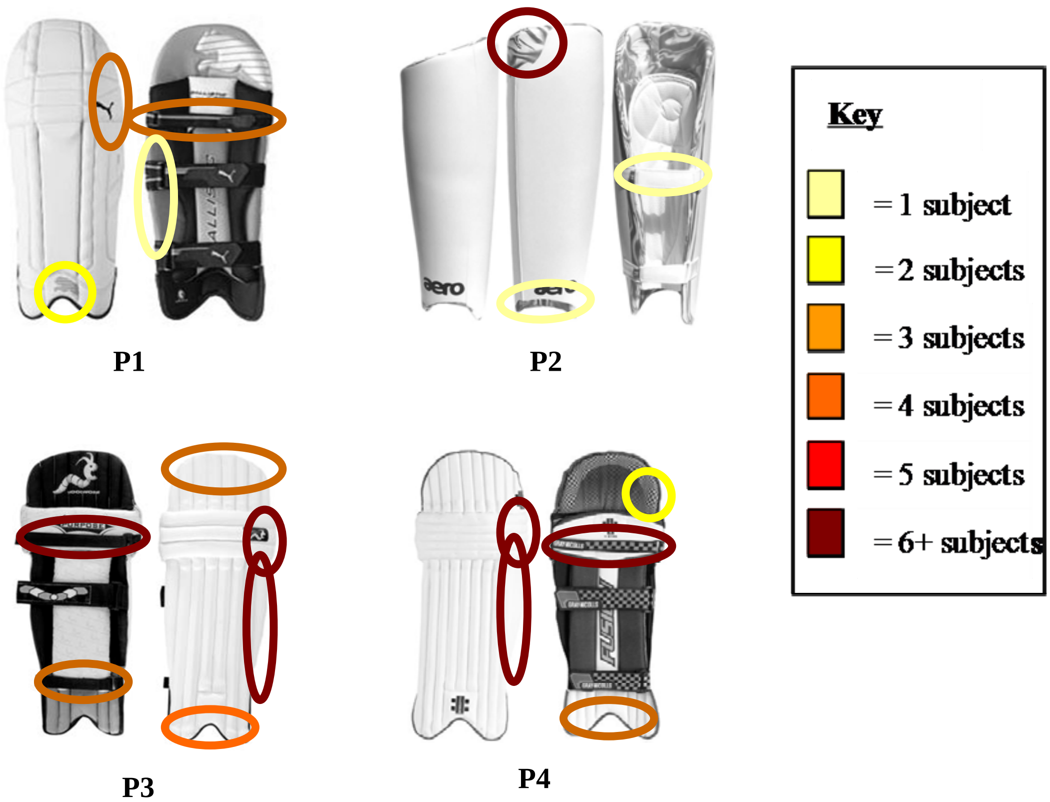


Figure 6. 24: Illustrates the areas identified as causing significant discomfort and the number of subjects that highlighted each specific area

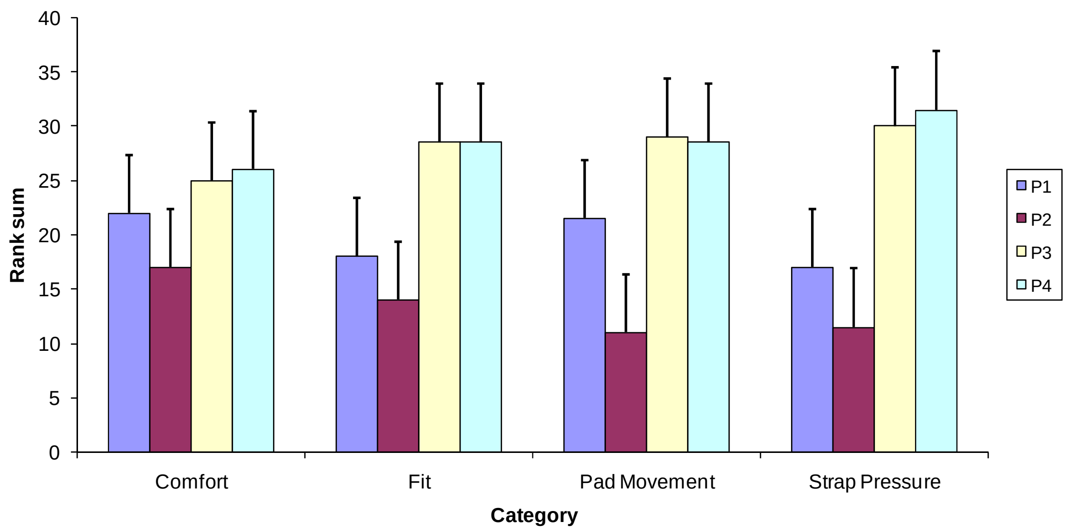


Figure 6. 25: Rank sum results for each pad in relation to comfort, fit, pad movement and strap pressure +1 LSD_{rank}

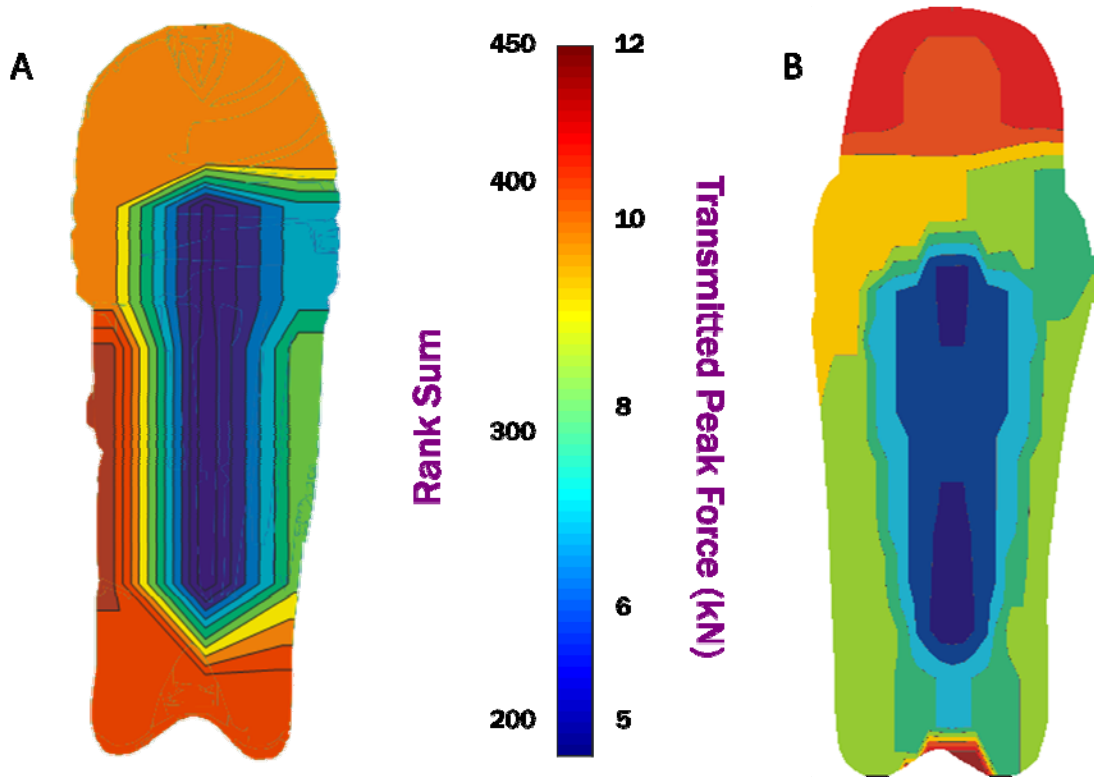


Figure 7. 1: Comparison between A) areas perceived to need the most protection and B) protection provided by a typical pad from a 31.3m/s impact (Webster *et al.* 2009)

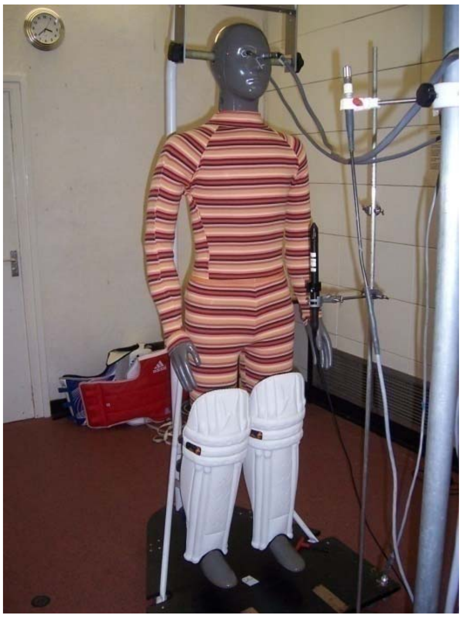


Figure 7. 2: Thermal manikin testing of P3

Measurement	Measurement (mm)					
	Pad					
	P1	P2	P3	P4	P5	P6
A	250	200	260	241	240	249
B	645	600	670	693	650	688
C	440	412	434	455	460	458
D	235	78	247	234	278	235
E	35	40	53	43	40	52
F	28	-	24	27	28/50	26
G	53	36	49	51	53	50
H	53	38	48	51	53	50

Figure 7. 3: Comparison of dimensions for P1 to P6

Figure 7. 4: Examples of motorcycle (Northern accessories, 2009) and firearms knee pads (Sunshines, 2009)

Figure 7. 5: Example of baseball catchers leg guards (Smarter, 2009)

Figure 7. 6: Concept design including Nylon and Polyester straps.

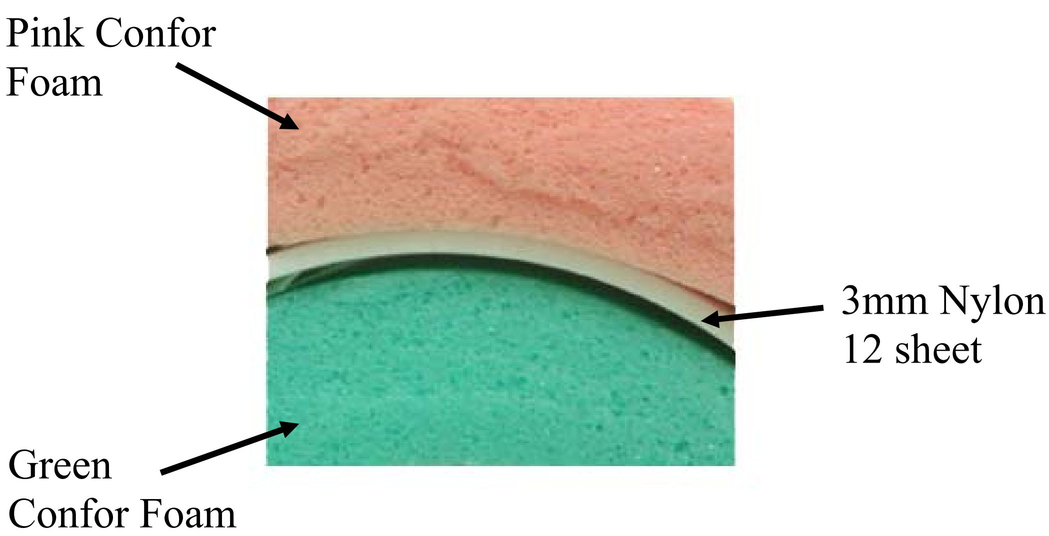


Figure 7. 7: Green and pink Confor foam test sample with a 3mm AM sheet

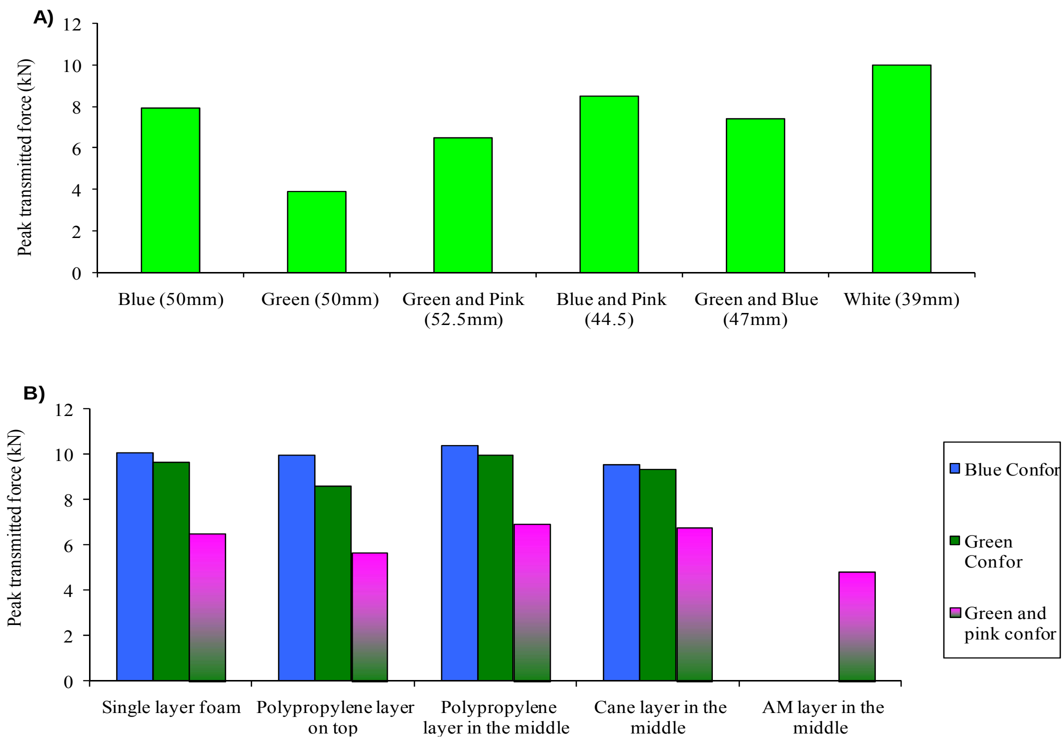


Figure 7. 8: Peak transmitted force at 31.3m/s for A) different combinations of Confor foams and EVA foam and B) different grades of Confor foams without an insert, with a polyurethane top layer, a polypropylene insert in the middle, canes in the middle and a Nylon 12 insert in the middle of the foam (Walker, 2009)

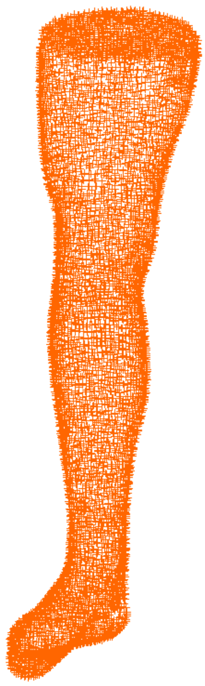


Figure 7. 9: Point cloud taken from the 3D body scan of the leg

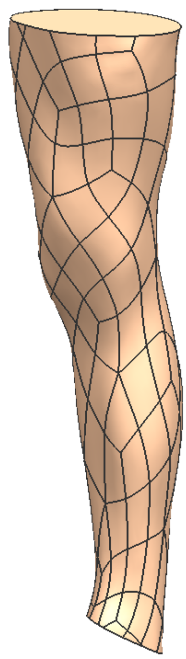


Figure 7. 10: Surfaced leg made from the point cloud

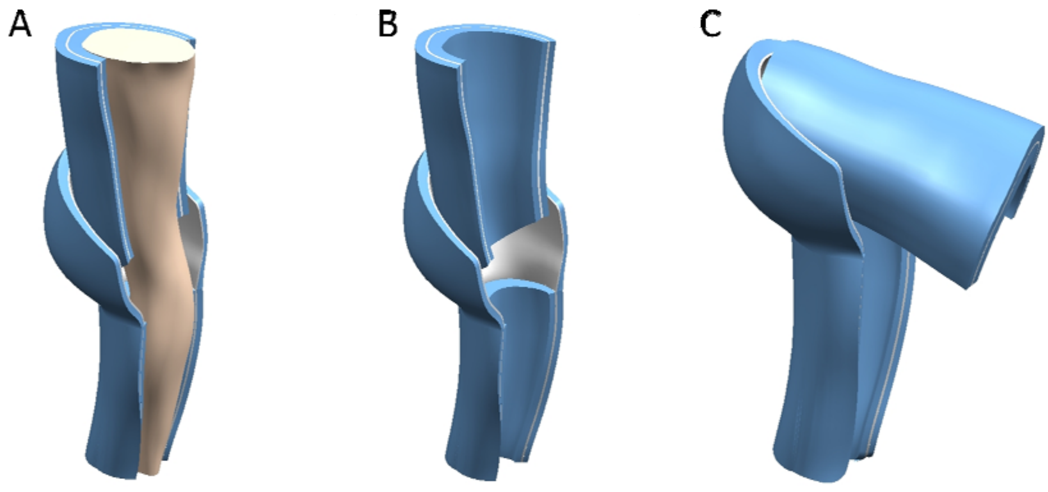


Figure 7. 11: Concept design A) wrapped around a leg, B) in a straight leg position and C) bent to 120°

Appendices

Appendix 1: Interview guideline

Interview Guidelines

1. Was there any noticeable difference between the pads used today regarding comfort? If so what?
2. What is your overall opinion of existing cricket pads regarding their comfort
3. Give a time line regarding the pads from putting them on to taking them off when batting for a long period of time.
4. What encouraged you to purchase your current set of pads?
5. What features do you particularly like/ look for when choosing a pad and why?
6. What features would deter you from using a certain pad?
7. What is the biggest problem with wearing cricket pads?
8. Do you feel cricket pads can effect your performance if so, how?
9. When wearing pads for a length of time do any feelings of discomfort become more apparent?
10. How have cricket pads improved since you began to play?
11. What would you like to see improve with current cricket leg guards?
12. As a group could you rate the pads in order as if you were choosing a pad for the team and explain why you placed the pad where you did.

Appendix 2: AHP online questionnaire

Cricket Pad Comfort Questionnaire

Thank you for participating in this survey for my research. I am a PhD student at Loughborough University investigating the perception of comfort and fit of cricket legguards. Within this survey we are interested in what characteristics of a cricket pad you find most important in regards to comfort. For more information about my research, please feel free to contact me or visit the Sports Technology Research Group for other sports related research performed at Loughborough.

For this survey, you will be presented with different question formats, so please read the instructions for each question carefully. Once you feel happy with your answers press the submit button at the bottom of the page.

Many thanks,

James Webster

J.M.F.Webster@lboro.ac.uk

Age:

Gender: Male Female

Level played at (or equivlant): International County University Team

Batting position: 1-4 5-7 8+

What leg guard do you currently use?

Next

Cricket Pad Comfort Questionnaire

Six factors have been seen to affect the comfort of players whilst wearing cricket pads, before answering the following questions please look at what each factor incorporates. Once you are happy that you know what is meant by each factor click continue.

Factors

1 Heat balance Incorporates how the pad allows heat to be removed from the leg preventing sweating and over heating.

2 Material feel involves the feel of the material caused by the interaction between the pad and the skin.

3 Fit is determined by how flexible the pad is and whether it shapes to the leg or not, whether the pad restricts movement and how the pad is secured to the leg.

4 Weight How light or heavy the pad is.

5 Aesthetics Incorporates the shape and style of the pad, the colour of it, and any design features such as graphics, and stitching.

6 Protection Includes whether there are any weaknesses within the pad, how exposed the leg is to the ball and how much padding there is.

Back Next

Cricket Pad Comfort Questionnaire

1. Within each of the 5 pairs listed below, move the bars accordingly to show how much more important one factor is than the other.

(If slide bars do not appear allow blocked contents)

	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	
Aesthetics								Material feel
Fit								Weight
Material feel								Protection
Heat balance								Weight
Protection								Aesthetics

Back Next

Cricket Pad Comfort Questionnaire

2. Within each of the 5 pairs listed below, move the bars accordingly to show how much more important one factor is than the other.

(If slide bars do not appear allow blocked contents)

Aesthetics	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Weight
Fit	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Protection
Heat balance	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Aesthetics
Weight	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Material Feel
Fit	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Heat balance

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Cricket Pad Comfort Questionnaire

3. Within each of the 5 pairs listed below, move the bars accordingly to show how much more important one factor is than the other.

(If slide bars do not appear allow blocked contents)

Aesthetics	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Fit
	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Heat balance
Heat balance	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Protection
Fit	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Material Feel
Protection	Much more important	More important	Slightly More important	Equal importance	Slightly More important	More important	Much more important	Weight

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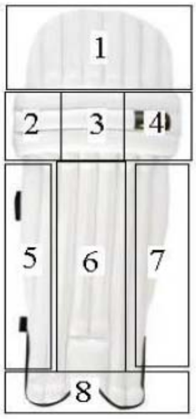
Cricket Pad Comfort Questionnaire

4. Where do you require the most protection (Image of right handed batsmans front leg guard)?

Number the zones 1-8 in order of required protection (1=Most, 8=Least)



Zone 1	1
Zone 2	2
Zone 3	3
Zone 4	4
Zone 5	5
Zone 6	6
Zone 7	7
Zone 8	8

Back Next

Cricket Pad Comfort Questionnaire

4. How do you rate the look of different areas of each pad?

	Shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good
	Shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good
	Shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good
	Shape of pad	V. Good
	Above the knee	V. Good
	Knee area	V. Good
	Shin area	V. Good

Back Next

Cricket Pad Comfort Questionnaire

6. How many straps do you prefer? 2 or 3

7. Do you prefer pads to have a knee roll? Yes or No

8. What characteristics would your ideal pad have?

Thank you for your participation

Back Submit

Appendix 3: Cricket batting pad questionnaire

Cricket Batting Pads Questionnaire

Section 1

1	How long have you been playing cricket for? (In years).	<1 ☐	1-2 ☐	2-3 ☐	3+ ☑
2	To what standard have you played cricket?		Club ☐	County ☐	Country ☑
3	How many different batting pads have you owned?	0 ☐	1 ☐	2 ☐	3+ ☑

4 When choosing which batting pads, how important do you rate the following factors?

	1 - Very unimportant	2 - Unimportant	3 - Somewhat important	4 - Important	5 - Very important
Price	1 ☐	2 ☐	3 ☑	4 ☐	5 ☐
Make	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐
Comfort	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐
Protection	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐
Flexibility	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐
Shape	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐
Aesthetics	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐
Fit	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐

5	Would you say that wearing batting pads changes how you run?	Yes ☑	No ☐	Don't know ☐
6	When wearing batting pads how (if at all) do they affect the speed of your running?	Slow down ☑	Same speed ☐	Faster ☐
7	Do you think that wearing batting pads restricts the range of movement at your knee?	Yes ☑	No ☐	Don't know ☐
8	Do you think that wearing batting pads restricts the range of movement at your ankle?	Yes ☐	No ☑	Don't know ☐

9 If you answered yes to question 7 and/ or 8, answer to question 9 for the appropriate joint:

How much do you feel that your range of movement is restricted on a scale of 1 to 5 described below?

	1 – Very slightly	2 - Slightly	3 – Noticeable amount	4 - Significantly	5 – Very significantly
Knee	1 ☐	2 ☐	3 ☑	4 ☐	5 ☐
Ankle	1 ☐	2 ☐	3 ☑	4 ☐	5 ☐

10	Rank the 8 different cricket shots, in order of how much restriction you feel there is during the movement due to wearing batting pads.							
	1 – Least restriction	2	3	4	5	6	7	8 – Most restriction
Full Toss	1 ☑	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☑	8 ☐
Sweep	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☑	8 ☑
Backward defensive	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☑	7 ☐	8 ☐
Backward attack	1 ☐	2 ☐	3 ☐	4 ☐	5 ☑	6 ☐	7 ☐	8 ☐
Pull	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☑	8 ☐
Forward defensive	1 ☐	2 ☐	3 ☐	4 ☑	5 ☐	6 ☐	7 ☐	8 ☐
Drive	1 ☐	2 ☑	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐
Hook	1 ☐	2 ☐	3 ☑	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐

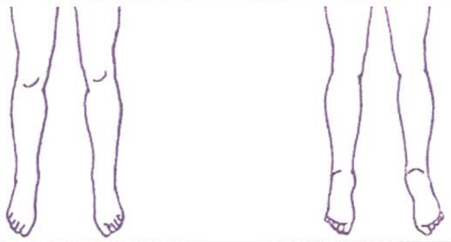
Appendix 4: Comfort questionnaire

2 RH

Comfort and Fit Questionnaire

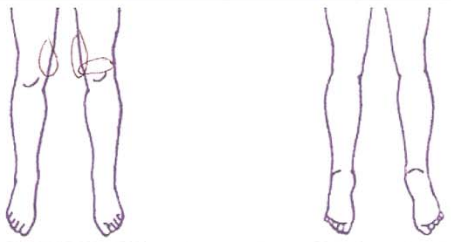
Pad: Puma

1	How comfortable did you find the batting pads to wear on a scale of 1-5?			
1 - Very uncomfortable	2 - Uncomfortable	3 - Somewhat comfortable	4 - Comfortable	5 - Very comfortable
1 ☐	2 ☐	3 ☐	4 ☑	5 ☐

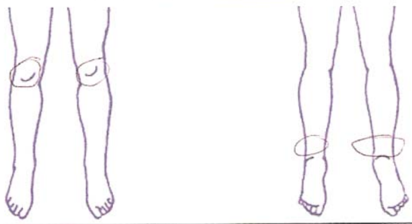
2	If you found the batting pads uncomfortable, circle any areas where you felt discomfort on the diagram: 
3	Mark on the line scale how much you felt that the pads were restricting your range of motion. No restriction — Some restriction — Maximal restriction
4	Where (if at all) did you feel the batting pads were restricting you and why do you think this is? ankle

Pad: Aero

1	How comfortable did you find the batting pads to wear on a scale of 1-5?			
1 - Very uncomfortable	2 - Uncomfortable	3 - Somewhat comfortable	4 - Comfortable	5 - Very comfortable
1 ☐	2 ☐	3 ☐	4 ☑	5 ☐

2	If you found the batting pads uncomfortable, circle any areas where you felt discomfort on the diagram: 
3	Mark on the line scale how much you felt that the pads were restricting your range of motion. No restriction — Some restriction — Maximal restriction
4	Where (if at all) did you feel the batting pads were restricting you and why do you think this is?

Pad: Woodworm

1	How comfortable did you find the batting pads to wear on a scale of 1-5?				
	1 - Very uncomfortable	2 - Uncomfortable	3 - Somewhat comfortable	4 - Comfortable	5 - Very comfortable
	1 ☐	2 ☐	3 ☑	4 ☐	5 ☐
2	If you found the batting pads uncomfortable, circle any areas where you felt discomfort on the diagram: 				
3	Mark on the line scale how much you felt that the pads were restricting your range of motion. No restriction — Some restriction — Maximal restriction				
4	Where (if at all) did you feel the batting pads were restricting you and why do you think this is? knee and ankle straps				

Appendix 5: Vicon code for cluster markers

MKR Label
[Autolabel]

RASI	Right SacroIliac Anterior
RPSI	Right SacroIliac Posterior
RHJC	Right Hip Joint Centre
HJC	Centre between Joint Centres
RKNEL	Right Knee Lateral
RKNEM	Right Knee Medial
RKNEJC	Right Knee Joint Centre (Actual)
RKNELI	Right Knee Lateral (Imaginary - I)
RKNEMI	Right Knee Medial (I)
RKNEJCI	Right Knee Joint Centre (I)
RTHII	Right Thigh Inferior
RTHIS	Right Thigh Superior
RTHIA	Right Thigh Anterior
RKNELC	Right Knee Lateral (Cluster)
RKNEMC	Right Knee Medial (Cluster)
RKNEJCC	Right Knee Joint Centre (Cluster)
RANKL	Right Ankle Lateral
RANKM	Right Ankle Medial
RANKJC	Right Ankle Joint Centre
RANKLI	Right Ankle Lateral (I)
RANKMI	Right Ankle Medial (I)
RANKJCI	Right Ankle Joint Centre (I)
RMTPL	Right MetatarsoPhalangeal Lateral
RMTPM	Right MetatarsoPhalangeal Medial
RMTPJC	Right MetatarsoPhalangeal Joint Centre
RHL	Right Heel
LASI	Left SacroIliac Anterior
LPSI	Left SacroIliac Posterior
LHJC	Left Hip Joint Centre
LKNEL	Left Knee Lateral
LKNEM	Left Knee Medial
LKNEJC	Left Knee Joint Centre (Actual)
LKNELI	Left Knee Lateral (I)
LKNEMI	Left Knee Medial (I)
LKNEJCI	Left Knee Joint Centre (I)

LTHII Left Thigh Inferior
LTHIS Left Thigh Superior
LTHIA Left Thigh Anterior
LKNELC Left Knee Lateral (Cluster)
LKNEMC Left Knee Medial (Cluster)
LKNEJCC Left Knee Joint Centre (Cluster)

LANKL Left Ankle Lateral
LANKM Left Ankle Medial
LANKJC Left Ankle Joint Centre
LANKLI Left Ankle Lateral (I)
LANKMI Left Ankle Medial (I)
LANKJCI Left Ankle Joint Centre (I)

LMTPL Left MetatarsoPhalangeal Lateral
LMTPM Left MetatarsoPhalangeal Medial
LMTPJC Left MetatarsoPhalangeal Joint Centre
LHL Left Heel

RHJC,LHJC
RHJC,RKNEJCI
RKNEJCI,RANKJCI
LHJC,LKNEJCI
LKNEJCI,LANKJCI
RHJC,RKNEJC
LHJC,LKNEJC
RKNEJC,RANKJC
LKNEJC,LANKJC
RANKJCI,RMTPJC
LANKJCI,LMTPJC
RANKJC,RMTPJC
LANKJC,LMTPJC

RKAngle Right Knee Angle (I)
LKAngle Left Knee Angle (I)
RKAngleA Right Knee Angle (A)
LKAngleA Left Knee Angle (A)

RAAngle Right Ankle Angle (I)
LAAngle Left Ankle Angle (I)
RAAngleA Right Ankle Angle (A)
LAAngleA Left Ankle Angle (A)

{*VICON - RANGE OF MOTION CODE - CRICKET*}

{*==*}

```
{* Define Optional Points - include all*}
{* In order: Hips, Knee, Ankle, Triads, Feet *}

OptionalPoints(RASI,RPSI,RHJC,HJC)
OptionalPoints(RKNEL,RKNEM)
OptionalPoints(RANKL,RANKM,RANKJC)
OptionalPoints(RTHIS,RTHII,RTHIA)
OptionalPoints(RMTPL,RMTPM,RHL)
OptionalPoints(LASI,LPSI,LHJC)
OptionalPoints(LKNEL,LKNEM)
OptionalPoints(LANKL,LANKM,LANKJC)
OptionalPoints(LTHIS,LTHII,LTHIA)
OptionalPoints(LMTPL,LMTPM,LHL)

{* Defining Upper/Lower Leg Clusters *}
{* R = Right, L = Left, U = Upper, Lo = Lower, Le = Leg, C = Cluster *}

    RULeC = [RTHIS,(RTHIS+RTHII)/2-RTHIS,RTHIA-(RTHIS+RTHII)/2]
    LULeC = [LTHIS,(LTHIS+LTHII)/2-LTHIS,LTHIA-(LTHIS+LTHII)/2]
    RLoLeC = [RHL,RHL-(RMTPL+RMTPM)/2,RMTPL-(RMTPL+RMTPM)/2]
    LLoLeC = [LHL,LHL-(LMTPL+LMTPM)/2,LMTPL-(LMTPL+LMTPM)/2]

{* RUN A STATIC TRIAL FIRST *}
{*==========================================*}

If $Static==1 then
```

{*Save Average Length of Leg as a Parameter*}

```
RKNEJC = (RKNEL+RKNEM)/2
RANKJC = (RANKL+RANKM)/2
LKNEJC = (LKNEL+LKNEM)/2
LANKJC = (LANKL+LANKM)/2
RMTPJC = (RMTPL+RMTPM)/2
LMTPJC = (LMTPL+LMTPM)/2

RLegLength = DIST(RASI,RKNEJC)+DIST(RKNEJC,RANKJC)
LLegLength = DIST(LASI,LKNEJC)+DIST(LKNEJC,LANKJC)
MP_LegLength = (RLegLength+LLegLength)/2
PARAM(MP_LegLength)
```

{*Finding Local position of Knee Markers relative to Thigh Triad*}

```
$%RKNELI = RKNEL/RULeC
$%RKNEMI = RKNEM/RULeC
$%LKNELI = LKNEL/LULeC
$%LKNEMI = LKNEM/LULeC
```

{*Finding local position of ankle markers relative to foot triad*}

```
$%RANKLI = RANKL/RLoLeC
$%RANKMI = RANKM/RLoLeC
$%LANKLI = LANKL/LLoLeC
$%LANKMI = LANKM/LLoLeC
```

{*Saving the following local coordinate parameters*}

```
PARAM($%RKNELI,$%RKNEMI,$%LKNELI,$%LKNEMI,$%RANKLI,$%RANKMI,$%LANKLI,$%LANKMI)

EndIf



{*Hip JC - uses Davis et al. 1991*}
{*=============================================*}

SACR = (LPSI+RPSI)/2
PELF = (LASI+RASI)/2

Pelvis = [PELF, RASI-LASI, SACR-PELF, xzy]

RATD = 0.1288*MP_LegLength-48.56
LATD = RATD

C = MP_LegLength*0.115-15.3
InterASISDist = DIST(LASI,RASI)
aa = InterASISDist/2
mm = 14
COSB = 0.951
SINB = 0.309
COST = 0.880
SINT = 0.476
COSTSINB = COST*SINB
COSTCOSB = COST*COSB
```

```
RHJC = {-C*SINT+aa, C*COSTSINB-(RATD+mm)*COSB, -C*COSTCOSB-(RATD+mm)*SINB}*Pelvis

LHJC = {C*SINT-aa, C*COSTSINB-(LATD+mm)*COSB, -C*COSTCOSB-(LATD+mm)*SINB}*Pelvis

HJC = (RHJC+LHJC)/2


OUTPUT(RHJC,LHJC,HJC)



{*Knee and Ankle JCs from Virtual Markers*}

{*==============================================*}


If $Static==0 then

{*transforming from local co-ordinates to global co-ordinates with '*' function*}


    RKNELI = $%RKNELI*RULeC

    RKNEMI = $%RKNEMI*RULeC

    LKNELI = $%LKNELI*LULeC

    LKNEMI = $%LKNEMI*LULeC


    RANKLI = $%RANKLI*RLoLeC

    RANKMI = $%RANKMI*RLoLeC

    LANKLI = $%LANKLI*LLoLeC

    LANKMI = $%LANKMI*LLoLeC


EndIf
```

RKNEJCI = (RKNELI+RKNEMI)/2

LKNEJCI = (LKNELI+LKNEMI)/2

RANKJCI = (RANKLI+RANKMI)/2

LANKJCI = (LANKLI+LANKMI)/2

RKNEJC = (RKNEL+RKNEM)/2

RANKJC = (RANKL+RANKM)/2

LKNEJC = (LKNEL+LKNEM)/2

LANKJC = (LANKL+LANKM)/2

OUTPUT(RKNELI,RKNEMI,LKNELI,LKNEMI,RANKLI,RANKMI,LANKLI,LANKMI)

OUTPUT(RKNEJCI,LKNEJCI,RANKJCI,LANKJCI)

OUTPUT(RKNEJC,RANKJC,LKNEJC,LANKJC)

{*Limb Segments from Virtual Markers*}

{* ===*}

{*Foot*}

RMTPJC = (RMTPL+RMTPM)/2

LMTPJC = (LMTPL+LMTPM)/2

RANKJC = (RANKL+RANKM)/2

LANKJC = (LANKL+LANKM)/2

RKNEJC = (RKNEL+RKNEM)/2

```
LKNEJC = (LKNEL+LKNEM)/2

RFoot = [RANKJCI,RMTPJC-RANKJCI,RANKLI-RANKJCI,XYZ]
LFoot = [LANKJCI,LMTPJC-LANKJCI,LANKLI-LANKJCI,XYZ]
NRMTPJC = RMTPJC+13*RFoot(1)-27*RFoot(2)
NLMTPJC = LMTPJC+13*LFoot(1)-27*LFoot(2)
RFT = [RANKJCI,NRMTPJC-RANKJCI,RANKLI-RANKJCI,XYZ]
LFT = [LANKJCI,NLMTPJC-LANKJCI,LANKJCI-LANKLI,XYZ]

OUTPUT(RMTPJC,LMTPJC)

{*Tibia*}

RTib = [RKNEJCI,RANKJCI-RKNEJCI,RANKLI-RANKJCI,XYZ]
LTib = [LKNEJCI,LANKJCI-LKNEJCI,LANKLI-LANKJCI,XYZ]

{*Femur*}

RFem = [RHJC,RKNEJCI-RHJC,RKNELI-RKNEJCI,XYZ]
LFem = [LHJC,LKNEJCI-LHJC,LKNELI-LKNEJCI,XYZ]

{*Limb Segments from Real Markers*}
{* ============================================*}
{*'A' at end of each segment specifies Actual*}
```

{*Foot*}

RFootA = [RANKJC,RMTPJC-RANKJC,RANKL-RANKJC,XYZ]

LFootA = [LANKJC,LMTPJC-LANKJC,LANKL-LANKJC,XYZ]

NRMTPJCA = RMTPJC+13*RFootA(1)-27*RFootA(2)

NLMTPJCA = LMTPJC+13*LFootA(1)-27*LFootA(2)

RFTA = [RANKJC,NRMTPJC-RANKJC,RANKL-RANKJC,XYZ]

LFTA = [LANKJC,NLMTPJC-LANKJC,LANKJC-LANKL,XYZ]

{*Tibia*}

RTibA = [RKNEJC,RANKJC-RKNEJC,RANKL-RANKJC,XYZ]

LTibA = [LKNEJC,LANKJC-LKNEJC,LANKL-LANKJC,XYZ]

{*Femur*}

RFemA = [RHJC,RKNEJC-RHJC,RKNEL-RKNEJC,XYZ]

LFemA = [LHJC,LKNEJC-LHJC,LKNEL-LKNEJC,XYZ]

{*Joint Angles - Virtual/Real*}

{* ==*}

{*KNEE - between Femur/Tibia*}

RKAngle = <RTib,RFem,zxy>

LKAngle = <LTib,LFem,zxy>

RKAngleA = <RTibA,RFemA,zxy>

LKAngleA = <LTibA,LFemA,zxy>

{*ANKLE - between Tibia/Foot*}

RAAngle = <RFT,RTib,zxy>

LAAngle = <LFT,LTib,zxy>

RAAngleA = <RFTA,RTibA,zxy>

LAAngleA = <LFTA,LTibA,zxy>

OUTPUT(RKAngle,LKAngle,RKAngleA,LKAngleA,RAAngle,LAAngle,RAAngleA,LAAngleA)

Appendix 6: Leg guard comfort Questionnaire

Leg Guard Comfort Study

Subject No. …………………………….

Name…………………………………….

Date of Birth…………………………….

Nationality……………………………….

Sex……………………………….......

Playing level…..………………………

Batting position……………………….

Leg guard used………………………

Pad ….

Name of Pad: Puma

Initial Assessment

Final Assessment

Pad Width:

☐Much too Narrow ☐Too Narrow ☐Ideal ☐Too wide ☐Much too wide

Pad Length:

☐Much too short ☐Too short ☐Ideal ☐Too long ☐Much too long

Areas of discomfort

Please circle and number any areas causing discomfort on the image of the Leg guard, then describe cause in the space provided below.

Pad …

Name of Pad: Grey Nicholls

Initial Assessment

Final Assessment

Pad Width:

☐Much too Narrow ☐Too Narrow ☐Ideal ☐Too wide ☐Much too wide

Pad Length:

☐Much too short ☐Too short ☐Ideal ☐Too long ☐Much too long

Areas of discomfort

Please circle and number any areas causing discomfort on the image of the Leg guard, then describe cause in the space provided below.

Pad ….

Name of Pad: Aero

Initial Assessment

Final Assessment

Pad Width:

☐Much too Narrow ☐Too Narrow ☐Ideal ☐Too wide ☐Much too wide

Pad Length:

☐Much too short ☐Too short ☐Ideal ☐Too long ☐Much too long

Areas of discomfort

Please circle and number any areas causing discomfort on the image of the Leg guard, then describe cause in the space provided below.

Pad ….

Name of Pad: Woodworm

Initial Assessment

Final Assessment

Pad Width:

☐Much too Narrow ☐Too Narrow ☐Ideal ☐Too wide ☐Much too wide

Pad Length:

☐Much too short ☐Too short ☐Ideal ☐Too long ☐Much too long

Areas of discomfort

Please circle and number any areas causing discomfort on the image of the Leg guard, then describe cause in the space provided below.


PURPOSE

Assessment of overall Comfort

Mark pad A to D on the following scales, as shown in the example below.

Example

A D C B

Less Comfortable ←→ **More Comfortable**

Overall Comfort

Less Comfortable ←→ **More Comfortable**

Fit of the pad

Worse Fit ←→ **Better Fit**

Pad Movement

Lots of Movement ←→ **No Movement**

Strap Pressure

High Pressure ←→ **Low Pressure**

Restriction

Very Restrictive ←→ **No Restriction**

Weight

Heavy ←→ **Light**

Thank you for your participation

Appendix 7: Cricket batting pad PDS

Product Design Specification

Cricket Leg Pad

Current PDS version	1.3
Current document amendment date	30/11/09

Any changes made to this specification must be documented in the below table and the above current details updated.

Document Control History

PDS version	Date	Brief description of amendments	Amended by
1.0	29/10/09	Document creation	David Brackett
1.1	06/11/09	Updated contour maps added to section 2.1 Performance protection	David Brackett
1.2	30/11/09	Section 24 dynamic testing performance updated	Paul Walker
1.3	30/11/09	Updated section 2.1: scale on perceived protection contour map, section 13: PDS weight specification and section 18: knee flexion details	James Webster

9 Aim

The ultimate aim of the leg pad is to match or improve on the injury protection of existing pads while reducing the mass, bulk, and movement restriction.

10 Performance

2.1. Protection

- Negligible number of serious lower leg injuries in batsmen, therefore the leg pad protection should aim to match the impact absorption performance of existing pads.

Fit	31%	Perceived importance
Protection	24%	
Weight	17%	
Thermal	12%	
Aesthetics	8%	
Sensorial	8%	

Perceived areas of required protection:

- Increased protection down the centre of the knee and shin
- Less protection on the sides of the pad
- Least protection around the thigh and ankle

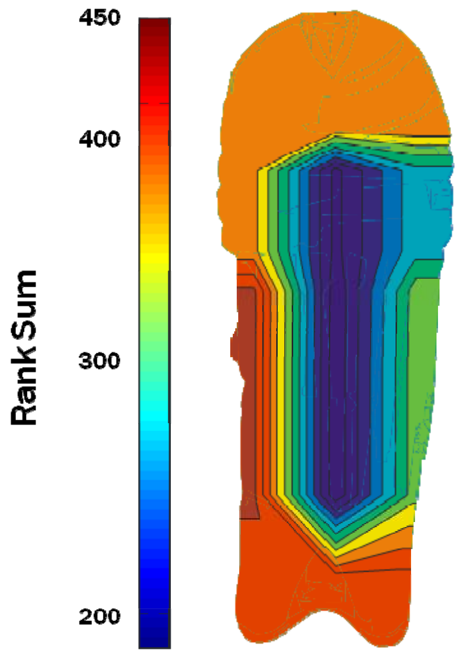


Figure 1 - Perceived protection levels

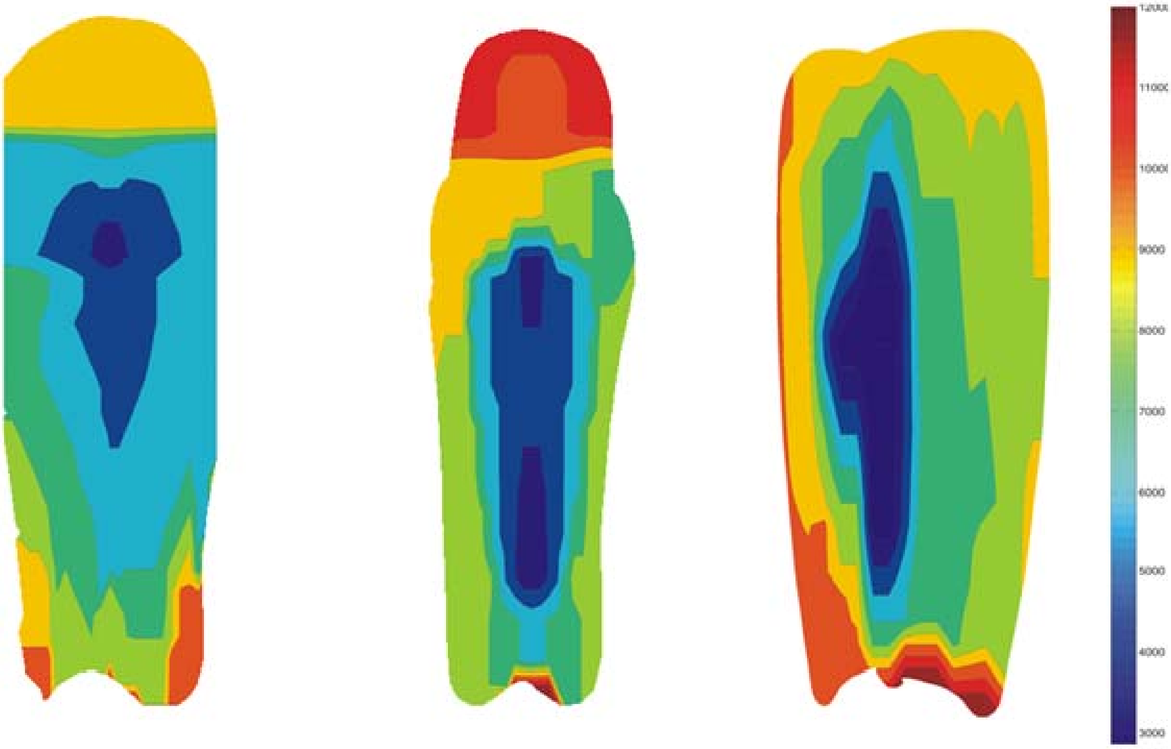


Figure 2 - Measured protection levels of a) Slazenger, b) Puma, and c) Aero pads

Quantified protection levels:

Zone	Max. Transmitted Force (kN)	
	British Standard (BS 6183-1:2000)	**PDS target from testing**
1	6	9.95
2	6	6.71
3	5	6.05
4	6	6.71
5	6	8.17
6	5	5.70
7	6	8.12
8	6	9.65

Table 1 - British standard and PDS target peak transmitted force

2.2. Comfort/Fit

Fit	31%
Protection	24%
Weight	17%
Thermal	12%
Aesthetics	8%
Sensorial	8%

Perceived

Fit:

- PDS target contact area >220cm^2.

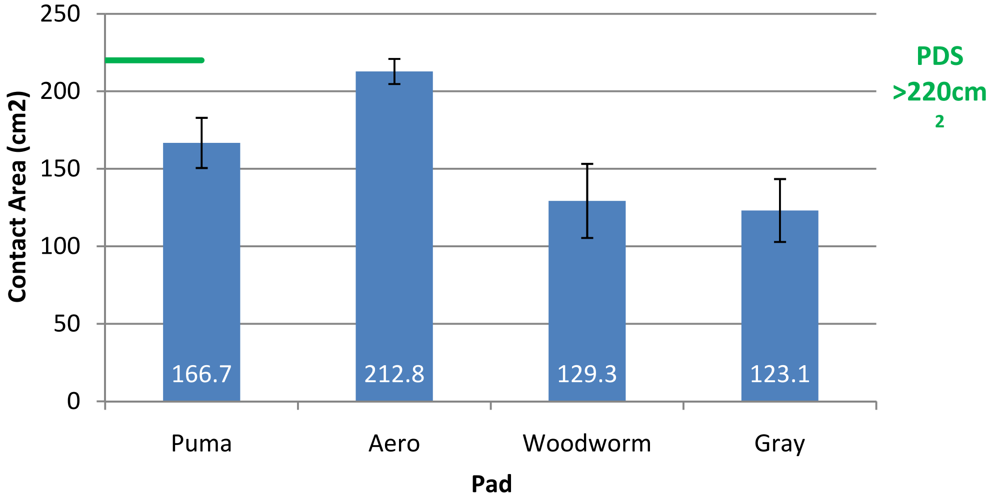


Figure 3 - Contact area comparison for competitors

- Strap design: Remove strap behind knee and increase strap area using a more flexible material
- Should restrict movement no more than existing commercially available pads for the same purpose and have other benefits in terms of comfort or the level of protection afforded.

Thermal:

Pad	Whole leg		Shin	
	Dry Insulation ($m^{2\circ}C/W$)	Wet Insulation (m^2Pa/W)	Dry Insulation ($m^{2\circ}C/W$)	Wet Insulation (m^2Pa/W)
Woodworm	0.18	29.2	0.36	150.92
Aero	0.18	26.43	0.55	984
Puma	0.19	32.4	0.33	106.26
PDS	0.18	26	0.33	106

Table 2 - Insulation comparison for competitors

Sensorial

- On impact the pad must not sound like a cricket bat being impacted.
- Straps should not be too rough to avoid abrasion of the skin.
- Users like the feel of real leather.

2.3. Running Speed

Should facilitate increased player movement freedom and increased running speed.

2.4. Technology integration

Measure:

- Force
- Pressure
- Peak Pressure/Force Location
- Displacement
- Impact Velocity
- Impact Time

Transmit via secure wireless system in real time, range 100m.
Integrated to allow full range of movement.

11 Environment

- Temperature range?
- Pressure range?
- Humidity?
- Shock loading?

During use, manufacture, storage, assembly, packaging, transportation, display?

12 Life in service (performance)

- Professional users – continual use, minimum 6 months.
- Semi professional – intermittent use, minimum 12-18 months.

13 Maintenance

- Must have the capability to be:
  1. Washed using conventional clothes washing equipment i.e. washing machine, hose pipe.
  2. Dried using non-specialised drying equipment.
- Functional maintenance: the consumer is not expected to perform any functional maintenance of the product when faulty.
- For sensor integration, to reduce the expense of waterproofing, it is allowable that some electronic components be removed/replaced such as the power source (battery) or control module.

14 Target product cost

- Most commercially available pads cost £20-100 retail.
- The pad should by competitive but a premium could be charged for significant improved performance.

15 Competition

- Products include: Slazenger, Gunn and Moore (GM), Puma, Aero, V-Lite, Canterbury, Gray Nicols, Readers
- Majority (~90%?) still use a cane covered structure, some developments in using more modern materials for canes and padding
- Puma represent a change in design whilst still selling product. No cane structure, just larger one piece areas of padding, also includes ability to alter shin and knee guard positions, customisation
- Aero pads, said to be able to control rebound of ball, single piece mould design. Lighter and thinner. Not selling, possibly because of such a different design, possibly not sponsoring top cricketers. Designed for speeds up to 100mph (from website)
- V sports V-lite batting pad in between. Pre-moulded shape, but traditional looking design. This is about as innovative and different as it gets.
- Differentiation between all other pads just due to looks and marketing

16 Shipping

17 Packing

Should use standard packaging.

18 Quantity

- Product largely bespoke and customised to the player so will be manufactured in batches of 1+.
- Several of the same design may need to be manufactured to provide a stock of spares.

19 Manufacturing facility

- The garment/s are required to utilise the design freedom and manufacturing flexibility of Additive Manufacturing (AM) to produce a customised and tailored protective personal system.
- Additional manufacturing or post processing techniques may be required to produce:
  1. the shell or skin outer of the protective garments i.e. PVC textile manufacturing.
  2. the fastening system i.e. injection moulding of clasps.
- Existing sewing techniques may be required for final assembly of the complete garment.
- Sensor technology integration?

20 Size

- Shape – Traditional pad, curved at the top, Needs to cut back in towards the thigh, preferably with a 3 roll knee. Also needs to wrap around the leg for maximum coverage and minimum impedance on running.
- Size- Must come well above knee to prevent feelings of being exposed to the ball as found by taller players using the oboe.

Figure 4 Measurement reference for size comparison

Measurement (mm)								
Competition								**PDS Target**
	W/worm	**Puma**	**Cant**	**Slaz**	**GM**	**Aero**	**Grays**	
A	260	250	240	248	249	200	241	
B	670	645	650	675	688	600	693	645 - 670
C	434	440	460	448	458	412	455	
D	247	235	278	245	235	78	234	<80 additional to leg
E	53	35	40	46	52	40	43	
F	24	28	28/50	23	26	-	27	
G	49	53	53	50	50	36	51	
H	48	53	53	52	50	38	51	

Table 3 - Size comparison with competitors

21 Weight

Fit	31%	Perceived
Protection	24%	
Weight	17%	
Thermal	12%	
Aesthetics	8%	
Sensorial	8%	

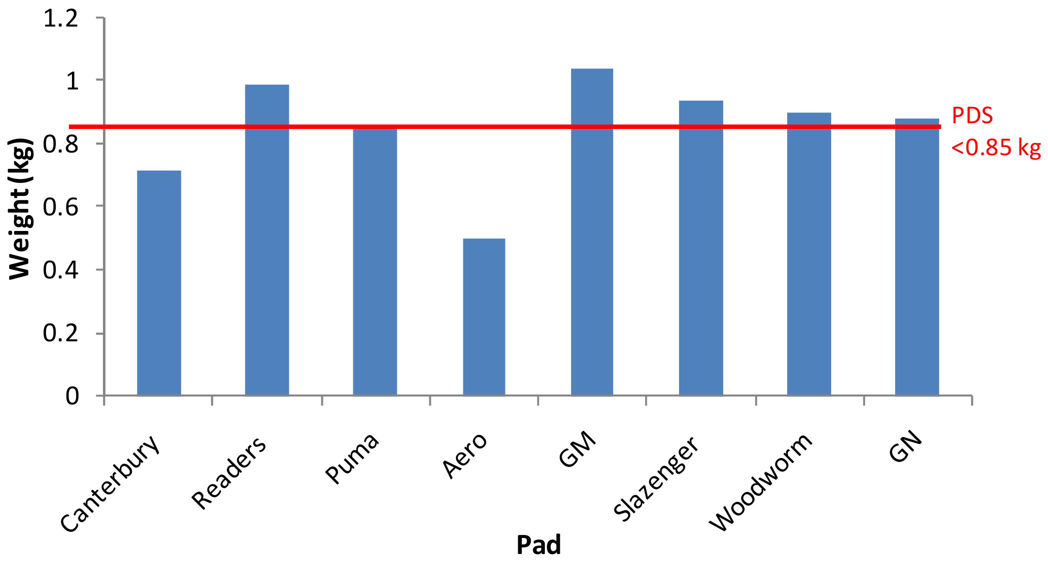


Figure 5 - Mass comparison with competitors

22 Aesthetics, appearance and finish

Fit	31%	Perceived
Protection	24%	
Weight	17%	
Thermal	12%	
Aesthetics	8%	
Sensorial	8%	

Traditional pad: Ridges on front, fabric/leather covering, curved top, does not narrow at the bottom.
New pad: The appearance of the pad should not dissuade the user from wearing it.

23 Materials

23.1 Properties of bulk material

Individual parts of the pad may have different properties depending on the design, but overall, the pad should exhibit the attributes listed below:

Property	**High**	**Low**	**Importance weighting**
Storage modulus (Energy absorbed)			
Loss modulus (Energy lost as heat)			
Tan delta (Damping)			
Tear strength			
Indentation force deflection			
Elongation at break			
Ball rebound			
Density			
Flammability			
Compressive strength			
Processing specific:			
Enthalpy of fusion			
Viscosity			
Thermal window			

Table 4 - Desired material properties

23.2 Properties of meso-structures

- Isotropic
- Similar compressive behaviour to foams

24 Product life span

- 1 to 2 seasons

25 Standards and specifications

- BS 6183-1:2000; Protective equipment for cricketers. General requirements
- BS 6183-1:2000; Protective equipment for cricketers. Leg protectors for batsmen, wicket-keepers and fielders, and thigh arm and chest protectors for batsmen

26 Ergonomics

- Must allow for at least 120° of flexion at the knee, whilst maintaining protection
- Percentage of the thigh covered
- Increased range of motion/ decreased impedance on running/ shots
- Decreased weight
- Increased moisture management

27 Customer

The initial customer base for this type of customised and tailored personal protective equipment are elite athletes.

28 Quality and reliability

29 Shelf life (storage)

30 Process Specifications

Additive manufacturing processes should be used in full or in part for production, specifically the selective laser sintering of powder.

31 Testing

Relevant standards:

- BS 6183-1:2000; Protective equipment for cricketers. General requirements
- BS 6183-1:2000; Protective equipment for cricketers. Leg protectors for batsmen, wicket-keepers and fielders, and thigh arm and chest protectors for batsmen

Impact Intensities:

- Release speed of ~100 mph, speed at batting end ~ 81 mph; ball: mass = 155-163 g, diameter = 224-229 mm (Penrose, 1976)

Dynamic Performance

1) Normal impact testing: Pad to be attached to rigid cylinder, normal impacts with hockey ball and inbound velocities of: 20, 30, 40 and 45 m/s. Pads to conform to following ranges:

Inbound Velocity (m/s)	Force (KN)	Contact Time (ms)	COR	Deformation (mm)
20	1	7 – 11	0.3 – 0.52	35 – 40
30	2 – 4	5 – 7.5	0.3 – 0.52	37 – 47
40	4 – 7	4 – 5.5	0.3 – 0.52	38 – 52.5
45	5.5 – 9	3.5 – 4.75	0.3 – 0.52	42 – 55

2) Oblique impact testing: - Pad to be attached to rigid cylinder, Oblique impacts with hockey ball at inbound velocity of 40 m/s at 4 positions: Position 1 = 0cm offset, Position 2 = 2.3 cm offset, Position 3 = 4.6 cm offset, Position 4 = 6.9 cm offset.

Position	Rebound Angle (deg)	Contact Time (ms)	COR	Pad Twist (deg)
1 (0 cm offset)	-10 – 10	6 – 8	0.35 – 0.5	0 – 2.5
2 (2.3 cm offset)	10 – 40	6 – 8	0.35 – 0.5	-2 – 4
3 (4.6 cm offset)	40 – 75	6.5 – 9	0.35 – 0.5	2.5 – 15
4 (6.9 cm offset)	65 – 110	6.5 – 10.5	0.35 – 0.5	4 – 25

3) Positional impact testing: Paul Walker to complete

- Using STI constructed custom rig
- Cricket pads are impacted by a 72mm diameter hockey ball of mass 160g (+-3g).
- 15-20 impact positions are selected over the surface of the cricket pad, selected to be representative of protection given but also to highlight any vulnerable areas
- 3 impacts carried out at each site, and an average is taken
- Average values should not exceed those given in the table below for each area
- Area definitions as is BS

Area	Peak force (kN)
Inner Knee	5
Outer Knee	10
Inner Shin	6
Outer Shin	8

Quasi Static Performance

- Instron based compression test (displacement: Ankle zone = 50 mm, Upper shin centre zone = 50 mm, Knee roll = 70 mm) using a cylindrical indentor of radius 45mm in diameter. The response should be bilinear and fall within the following ranges:

- Ankle zone:
  - Stiffness 1 = 5000 (-1250/+2500) N/m. (For 0-40 mm)
  - Stiffness 2 = 27000 (-10000/+23000) N/m. (For >40 mm)
- Upper shin centre zone:
  - Stiffness 1 = 5000 (-1250/+1250) N/m. (For 0-40 mm)
  - Stiffness 2 = 27000 (-10000/+18350) N/m. (For >40 mm)
- Knee roll:
  - Stiffness 1 = 3000 (-1250/+2500) N/m. (For 0-50 mm)
  - Stiffness 2 = 1500 (-10000/+23000) N/m. (For >50 mm)
  - At the maximum compression for each respective zone, contact pressure between pad and rigid plate, for a measured contact area of 72 mm x 200 mm
- Ankle zone: 37 – 55 KPa
- Shin centre zone: 30 – 55 KPa
- Knee roll: 24 – 30 KPa

Manufacturing testing
The AM component of the personal protective garment will be subjected to a visual inspection and comparison to the 3D CAD data used for its manufacture. Required accuracy of manufacturing?

Thermal testing
Thermal mannequin to be used to test dry and wet insulation.

32 Safety

Should provide a level of protection from injury consistent with existing leg pads.

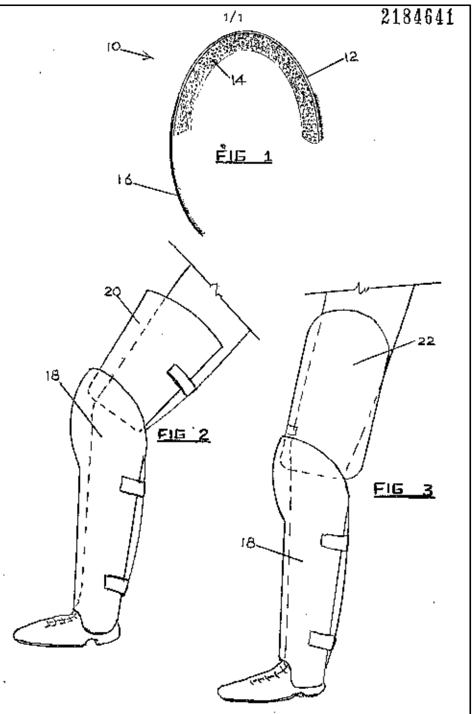
33 Patents

If a patent has lapsed, anyone can use the information but it can't be claimed as part of your invention.

AM structures approach:
No relevant patents found as yet.

Foam and AM insert combination with or without articulation:
Depending on the design, 3 potentially relevant patents found. Details provided below.

GB2184641 Padding for sporting purposes (1985)



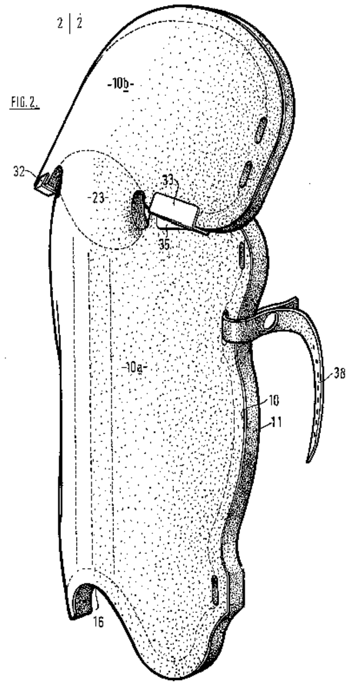
The invention relates to pads for cricket, hockey or the like which comprise a shell of rigid polymeric material which is nevertheless resilient to forces opening the shell and which is non-deformable in normal use, the shell being shaped to conform with a portion of the body to be protected such as the shins, thighs and the like, and having a laminate of cushioning material inside the shell.

CLAIMS

1. Padding for sport including a shell of rigid yet resilient (to shell-opening forces) non-deformable (in normal use) polymeric material shaped to conform with the part of the body to be protected and having a laminate of a cushioning material there inside.
2. The padding of claim 1 in which the padding comprises a first portion which covers the shin and knee and a second portion which covers the front of the thigh or portion thereof.
3. The padding of claim 1 orclaim2whichinclu des an integral zone conforming to the side or sides of the thigh to correspond with a conventional thigh pad.
4. Padding of any of the above claims in which the cushioning is a foamed polymeric material.
5. Padding of any of the above claims in which the shell includes a plurality of holes for ventilation.
6. The padding of claim 5 in which the shell is corrugated and the holes are located in the troughs.
7. Padding for sport substantially as described herein with reference to the accompanying drawings.

Status: Application withdrawn, taken to be withdrawn or refused after publication under section 16 (1).

GB2073009 Improvements in or relating to leg guards (1981)



Cricket pads and other leg guards for games players comprise a first, outer layer of plastics material which provides an impact resistant surface and a second, inner layer which provides a resilient padding for the leg of the user. The outer and inner layers, which can be in the form of a laminate, can respectively be a non-cellular polyethylene or polypropylene and a cellular polyethylene of polypropylene. The pad preferably has upper and lower portions adapted for hinge-like movement in the knee zone of the pad.

CLAIMS

1. A cricket pad or other leg guard formed from plastics material, comprising a first, outer layer which provides an impact-resistant surface, and a second, inner layer which provides a resilient padding for the leg of the user of the guard.
2. A leg guard according to Claim 1, in which said first and second layers are in the form of a laminate.
3. A leg guard according to Claim 2, in which the said laminate consists of said first and second layers.
4. A leg guard according to Claim 1,2 or 3, in which said first layer is of a non-cellular polyethylene or polypropylene.
5. A leg guard according to Claim 4, in which the first layer is of polyethylene having a specific gravity in the range from 0.91 to 0.99.
6. A leg guard according to any of the preceding claims, in which the said second layer is of a cellular polyethylene or polypropylene.
7. A leg guard according to Claim 6, in which said second layer is of polyethylene having a density in the range from 30 to 60 kg/m3.
8. A leg guard according to any of the preceding claims, in which the ratio of the thickness of said first and second layers is in the range from 1:12 to 1:8.
9. A leg guard according to any of Claims 2 to 8, which has been shaped from a flat sheet of said laminate under the influence of heat and moulding.
10. A leg guard according to Claim 1, in which the outer and inner layers are flame-bonded together and of substantially the same superficial dimensions; the outer layer is of non-cellular polyethylene having a specific gravity in the range from 0.91 to 0.99; the inner layer is of closed-cell cellular polyethylene having a density in the range from 30 to 60 kg/m3; and the ratio of the thickness of the outer layer to that of the inner layer is in the range from 1:9 to 1:11.
11. A cricket pad or other leg guard which comprises a lower portion to protect, in use, at least the shin of the user; and an upper portion to protect, in use, at least the lower part of the thigh of the user; and the lower and upper portions are disposed with reference to the overall dimensions of the leg guard so that, in use, the knee of the user is behind a knee zone connecting, or comprising contiguous border zones of, said lower and upper portions, the leg guard having flexibility in said knee zone to permit hinge-like movement of said lower and upper portions.
12. A leg guard according to Claim 11, in which said flexibility is provided by the use of slots or other re-entrant means extending inwardly from the side edges of the guard.

13. A leg guard according to Claim 12, in which said re-entrants each have an enlargement at their inner end.
14. A leg guard according to Claim 12 or 13, in which the curvature of the edge of the upper portion immediately above the re-entrant means is less than that of the edge of the lower portion immediately below said re-entrant means to facilitate said hinge-like movement.
15. A leg guard according to Claim 14, in which protective means are provided to protect said edges from damage by abrasion between them as a result of said hinge-like movement.
16. A cricket pad according to Claim 1 or 11, substantially as described herein with reference to the accompanying drawings.
17. A cricket pad substantially as described herein and substantially as shown in Figures 1 and 2 of the accompanying drawings.
18. A flat precursor for a cricket pad, substantially as described herein and substantially as shown in Figure 1 of the accompanying drawings.

Status: Patent ceased through non-payment of renewal fee.

WO0061244 Shock-absorbing composition and leg protector (2000)

The invention relates to a composition of at least four layers (1, 2, 3, 4) of alternating force distribution and force absorbing materials having the ability to distribute pressure and reduce the effects of a sudden impact. In a first aspect the composition is intended for use as a protection of body parts, such as the shin during football practice, whereas it can also be used during other athletic practices, e.g. soccer, cricket, riding, motor sports, skiing and ice hockey and used as a means for general damage prevention of a person or a property during professional practice.

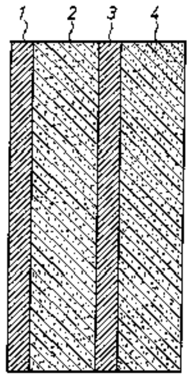


FIG. 1

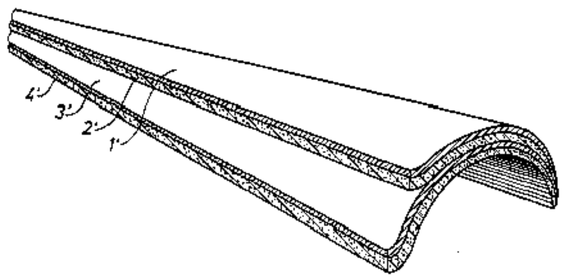


FIG. 2

CLAIMS

1. Material composition for protection against impacts, comprising an outer layer (1,1') of a force distributing material and further layers of alternating force absorbing and force distributing materials characterised in that the alternating layers are at least three (2,2', 3,3', 4,4'), and that said force distributing and force absorbing materials are elastic, wherein a force reduction is obtained when an outer force is applied to the composition.
2. A composition according to claim 1 characterised in that the force distributing and force absorbing materials result in a force reduction of at least 50%, wherein the force reduction is measured by means of the formula: Force reduction = (1-P/4000) x 100, and P = force of penetration.
3. A composition according to claim 1 characterised in that the force distributing and force absorbing materials result in a force reduction of at least 80%, wherein the force reduction is measured using the formula: Force reduction = (1-P/4000) x 100, and P = force of penetration.

4. A composition according to any of the preceding claims, characterised in that said hard material has a coefficient of elasticity of 0,5-100 GPa.
5. A composition according to any of the preceding claims, characterised in that said soft material has a coefficient of elasticity of 10-200 GPa.
6. A composition according to any of the preceding claims, characterised in that said hard material is a glass fibre composite or an aramide composite.
7. A composition according to any of the preceding claims, characterised in that said soft material is a cellular or foamed plastic with closed cells.
8. A composition according to claim 6, characterised in that said glass fibre composite has 3 or 4 fibre sheets.
9. A leg protective device comprising the composition according to any of the previous claims.
10. A leg protective device according to claim 9, characterised in that it includes an outer layer of a glass fibre composite and thereafter three alternating layers of polyethene foam, glass fibre composite and ethylene vinyl acetate copolymer, respectively.

Status: Lapsed.