SUBJECTIVE AND OBJECTIVE ASSESSMENT OF TENNIS RACKET PERFORMANCE IN PLAY

By

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CERTIFICATE OF ORIGINALITY

This is to certify that I am Responsible for the work submitted in this thesis, that the original work is my own except in acknowledgements or footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree

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ABSTRACT

Assessment of wielded implement performance is important to a variety of human endeavours and often critical to success in a sports context, particularly so in the game of tennis. Tennis racket design and manufacture is a multimillion business involving 10 major international companies. Tennis participation is currently estimated at around 60 million individuals worldwide. Thus the importance of optimum racket performance to maximise competitive advantage and minimise the risks of injury is clear.

This thesis presents work to enable advances in tennis racket performance with respect to player feel perception, measurement of physical phenomena and the correlation of these aspects within real play contexts.

To investigate feel perception a methodology was adapted from the existing literature. Interview testing was conducted to elicit a comprehensive range of tennis specific vocabulary. The end goal was to create a perception relationship map or 'feel map'. The inductive analysis was used to link all the related clustered themes identified from the vocabulary to sub and base themes describing the relationship. Further analysis introduced higher level general dimensions that unified common base themes. The resulting feel maps were created from both English and German sample groups, with a view to subsequent comparison.

To complete the map and broaden its application a wide scale questionnaire was distributed to a tennis playing population. The responses provided data indicating percentile use of selected vocabulary within the tennis community and the relative importance players associate with assorted perception groups. Visual representations of the data were introduced to the map for quick and easy use and an associated lexicon compiled to provide a reference for more detailed information.

The feel maps and lexicon provide users with a versatile tool in the form of a 'perception relationship model'. The map itself can act as an overall research guide

for future work in the field. The addition of percentile use and relative importance data mean the map can be used to create more informed and subtle player test questionnaires or as a design aid, with interdependency links indicating which additional factors should be considered or exploited for their influence on the characteristic areas in question. Interestingly the general dimensions of highest relative importance were sound and grip respectively. This may be due to the basic level of interaction between player and racket which ultimately has to be perceived either through the grip or from the sound. A perception test questionnaire was also created with the use of the feel map and later used to study the correlation between objective and subjective measures.

To best attain objective measures from the racket an innovative instrumentation system was created. Two alternative systems were designed and tested, the first based on wired instrumentation and data capture the second based on wireless technologies as these became available. Both systems were required to take measures of grip pressure and acceleration with 6 degrees of freedom.

The first system utilised uniaxial accelerometers mounted on an aluminium bracket, and a triaxial accelerometer inserted inside the butt of the racket arranged to allow measurement and calculation of acceleration from the required 6 degrees of freedom. The system could be adapted to include either TekScan multi-cell full grip coverage force measurement, or 2 single point higher sample rate single cell grip force sensors. All data was fed via 15 m of cable to data acquisition systems. This restricted the participants' freedom of movement and encumbered the racket and thus the systems application, making it unsuitable for extensive perception or fatigue testing.

The second system utilised a compact data logger with an integrated on board tri-axial accelerometer small enough to be mounted within the racket handle. A revised mount overcame the need for the aluminium throat bracket, moving the uniaxial accelerometers into a bulbous addition to the butt of the racket. The system was capable of capturing 8 channels simultaneously which allowed for the 6 accelerometers and two single cell grip force sensors to be located under the grip. The system was more difficult to adapt and maintain than the wired system, but improved freedom and reduced added weight to the racket made the system far more suitable for the planned perception and fatigue testing.

Fatigue testing conducted with the wireless device investigated the effect of full body fatigue on players' performance by monitoring the resultant effects in the racket. The protocol was based on the multistage fitness test, designed to progressively increase in difficulty until volitional fatigue. Heart rate data indicated that the protocol was successful in fatiguing the participants to a point at or near their VO2max. Unfortunately, with the wireless system in its early stages of development, the device failed mid way through testing. The limited data set that was collected indicated that technique was affected by fatigue. Further research is required to confirm this finding and to make comparisons between racket types during the fatiguing process.

The wireless device was adapted to make it more durable and reliable before the planned perception testing was conducted. A protocol was developed to investigate the affect of changing racket moment of inertia on player perception and physical measures. The test questionnaire developed from the feel map was used to evaluate player perception ratings of various elements of racket feel, and the wireless instrumentation system was used as part of methodology designed to compile a set of comparable physical data. A detailed analysis of the results revealed that there was some evidence of correlation between the perceptions of power, balance, flexibility and control and the moment of inertia of the racket. In a design optimisation context, however, more definitive correlations would be more useful. These would be expected to be found with future testing utilising a wider range of racket properties.

The research proves to a large extent the original hypothesis that through the use of non invasive instrumentation and improved player perception elicitation techniques it is possible to substantially and usefully improve the objective and subjective assessment of tennis racket performance in play to enable investigation of better design characteristics and fatigue related injury phenomena.

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GLOSSARY

Babolat RDC - racket diagnostics centre that allows measures of weight, moment of inertia, balance point, string tension and flexibility to be taken from a tennis racket.

Base theme – a common hub connecting closely related vocabulary and base themes that describe an element of tennis player perception

Breaking the angle – refers to a shot played in tennis when the player changes from playing cross court ground strokes to straight down the court 'along the line', usually in an effort to gain the attack and move in towards or 'approach' the net

Closed questioning – can be answered with either a single word or a short phrase

Clustering – the process of comparing and contrasting quotes with all the other quotes and emergent themes to unite quotes with similar meaning and separate quotes with different meanings

Conversational interview – an interview conducted with no predefined structure that is in essence a recorded open conversation.

EMG – electromyogram, the electrical activity of a muscle as recorded by an electromyograph

Feel map – a structured map that links tennis player vocabulary nodes to common base or sub themes that describe specific perceptions which are in turn linked to general dimensions to form hierarchal groups relating to a more general area of perception. Each perception group in the map may be linked to other groups via interdependencies whenever one has an impact on another and vice versa.

General dimension – a common hub connecting related base themes that describe a general area of tennis racket perception

Guided interview – largely conversational interview with some limited guidance from the interviewer

Inductive approach – an approach in which the end point or conclusion, in this case the feel map structure, is reached by the process of reasoning, in this case based upon the raw vocabulary data elicited from interview testing.

Interdependency link – connects areas of the feel map that are in someway dependent or affected by one another.

N6 QSR NUD*IST - software package used to classify and analyse transcribed text

Node – clustered quotes from transcribed text classified, or coded, under a generic descriptive title

Open questioning – encourages or requires a long answer or explanation

Order – the rank of feel map elements with lower order relating to elements that are most specific and basic: Usually interview quotes or nodes are of lowest order. Higher order relating to more general elements: General dimensions are of highest order.

Perception - awareness of the elements of environment through physical sensation

Perception elicitation tools – tools or methods that help stimulate and draw out player perceptions

Perception excitation scenarios – events that stimulate new, extreme or variations of player perceptions

Perception relationship model - a conceptual model of feel consisting of a 'feel map' and weighted lexicon

Polar moment of inertia – in a tennis racket the polar moment of inertia is the moment of inertia about the longitudinal axis that runs through the racket butt and the tip of the racket head and relates to the rackets resistance to twisting in the players hand.

Probing – questioning addressing specific issues introduced by the interviewee for clarification or classification.

Racket characteristic – a tangible feature of a tennis racket

Racket feel phenomenon - an occurrence or action in the racket that is perceptible by the senses

Racket perception - awareness of the elements and effects of a tennis racket through physical sensation

Relative importance – an importance rating of perceived elements of a tennis racket that is relative to all other elements

Smart racket – Instrumented tennis racket able to record various objective measures of its behaviour

Spearman ranking coefficient - a coefficient computed on scores that have been converted to rankings that indicate the strength of a correlation

Structured hierarchy – Groups of feel map elements organised by order and category, with higher order elements forming more central parts of categorical groups

Sub theme – a common lower order hub connecting closely related vocabulary that describes an element of tennis player perception

Swing weight - describes how heavy a racket feels when it is swung and essentially refers to the moment of inertia of the racket

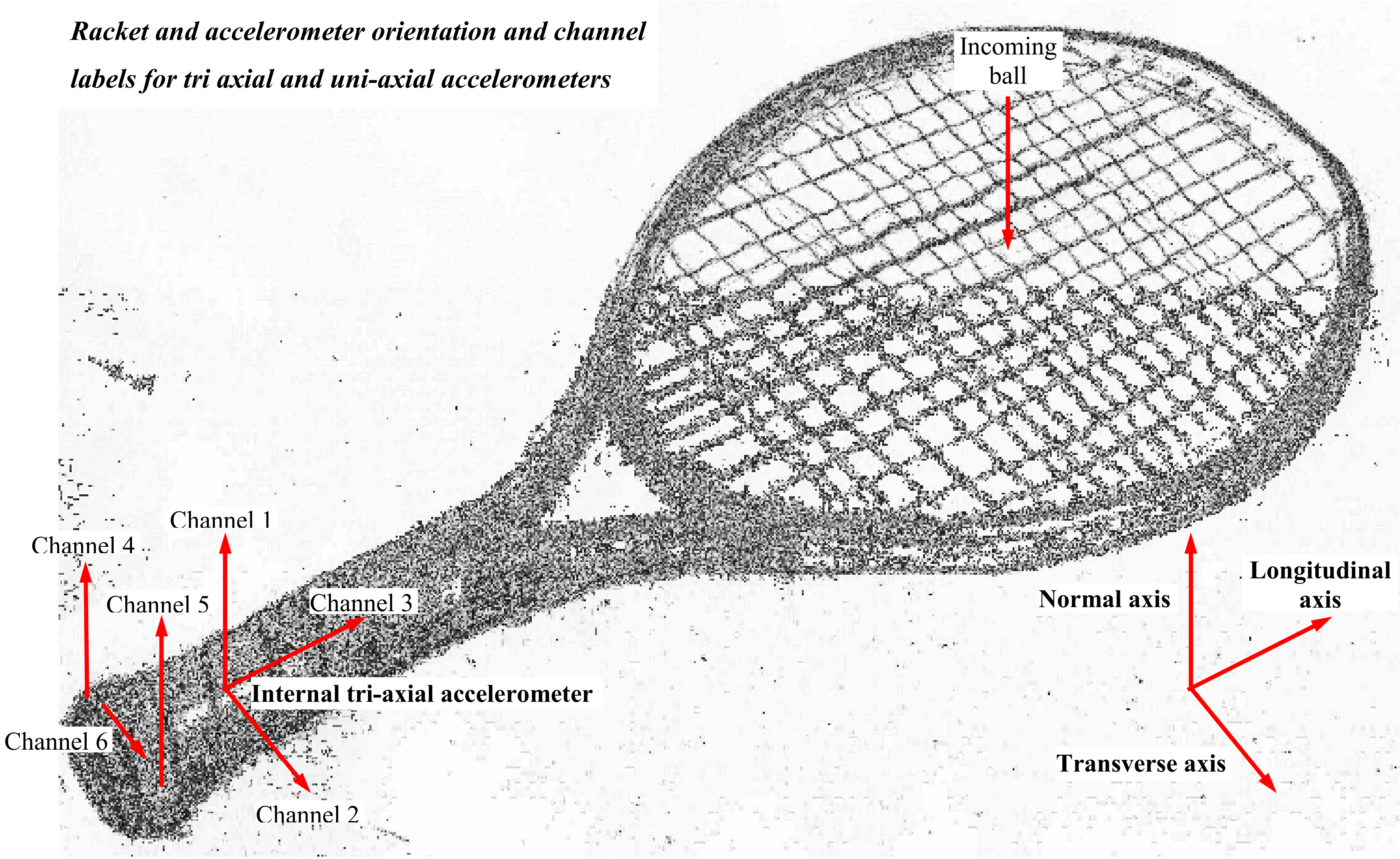
Tennis racket feel - to experience the effects of a tennis racket

VO2 – volume of oxygen uptake in the body measured in litres of oxygen per minute

$VO2_{max}$ – maximum possible volume of oxygen uptake in the body measured in millilitres of oxygen per kilogram of body mass per minute

Weighted lexicon – an inventory of terms with associated data that provides information on the weighting of relative importance or percentile use.

Racket and accelerometer orientation and channel labels for tri axial and uni-axial accelerometers



CHAPTER ONE

INTRODUCTION

1.1 Research Context

Tennis racket technology has evolved dramatically since its early beginnings when the game was played exclusively with wooden rackets. Over the years new materials have allowed the design and playing properties of rackets to develop, increasing the consistency of production and enhancing elements of performance, in particular, power, control and error reduction. The adoption and development of fibre reinforced thermosetting and thermoplastic materials over the last three decades has produced a the most substantial change in tennis racket performance. The inherent properties of the composite materials mean rackets can have far larger dimensions and can be lighter than any of the older wooden rackets and even extended metal rackets without sacrificing any structural strength or durability. Manufacturing consistency has also improved and racket stability and durability have similarly increased.

Although there have been a number of patents granted in this area these have proved inadequate to restrict composite racket infrastructure to only one brand. As a result composite technology is no longer a distinct product differentiator, as most manufacturers can produce competent designs.

More recently the application of science and research has pushed the technology of tennis further and further, with the relative gains in composite racket performance becoming gradually smaller year on year. If weight alone is considered the reduction in weight from the original wooden frames through to metal then composite frames was quite considerable reducing by up to half, where as more recent reductions in weight have been much more subtle reflecting only a small percentage of the whole racket weight. This coupled with pressure from governing bodies to slow down the game of tennis to encourage a more ‘spectator friendly’ sport, means that further work in this area may have its limits. Thus for manufacturers to gain a distinct advantage in the current market previously untapped applications of technology need to be investigated.

Elite athletes desire equipment that produces consistent results whilst producing extreme power and spin generation with minimal fatigue and an acceptable risk of injury. Their physical strength, skill and overall fitness are such that they can play with heavier, stiffer, more tightly strung rackets that in the hands of recreational players would be difficult and uncomfortable to use and so arguably result in a higher risk of injury.

The less competitive and able recreational players, that represent a high proportion of the tennis racket market, can still be seduced by ‘powerful’ racket designs. However, comfort, forgiveness (i.e. racket characteristics that accommodate poor play without detrimental performance or feel outcomes) and minimised risk of injury are arguably just as important if not more important to this market sector. Even so, rapid changes in racket design and technology have led to un-researched predictions of the effects of the changes in racket characteristics. For example discussions over whether much lighter composite rackets are good or bad for tennis elbow remain unresolved.

In particular lateral epicondylitis (tennis elbow) remains a problem for many recreational players. Injuries such as tennis elbow have been reported to affect as much as 40-50% of recreational players (Roetert et al. 1995). In addition to the obvious benefits for players, tennis racket manufacturers are very interested in the potential market for equipment boasting a reduced risk of injury. Any manufacturer that can deliver a racket that is proven to reduce the incidence of tennis elbow, the ‘holy grail’ of racket design, will have a significant marketing advantage. Thus there is a need for manufacturers to understand and quantify, through objective assessment, the interaction of the racket with the user not just the ball. Power and spin generation attributes are important, but perhaps should not be focused on at the expense of feel in terms of comfort, shock, vibration, fatigue levels and ultimately injury.

Not surprisingly therefore, discussions with H. Lammer (Head of Tennis Research, Head AG) and J. Kotze (Tennis Biomedical Projects Leader, Head AG) (2003) indicated that tennis injuries and in particular tennis elbow were a primary concern for tennis equipment manufacturers. Manufacturers had previously attempted to gain an advantage in a competitive market by claiming their design innovations reduced the incidence of injury. These claims were generally weak extrapolations based on unproven assumptions and generalisations as to the causes of injury and lack scientific proof. However, both racket and ball manufacturers must carefully consider whether their proposed changes/innovations increase the likelihood of injury before implementing them, as demonstrated by press coverage of the ITF's proposals to introduce a 6% bigger tennis ball.

Identifying the specific phenomena responsible for many tennis injuries, and in particular tennis elbow, has eluded researchers for some considerable time. Despite decades of research, an expert panel at the ITF convened international Tennis Science and Technology Conference in 2000 concluded that the cause had yet to be identified. A review commissioned by the ITF (Roussopoulos and Cooke 2000) concluded that a multi-disciplinary research programme to establish the scope for tennis racket design to exacerbate or prevent injury was needed.

A program of coordinated research at Loughborough University studying the combined effects of equipment mechanics and human biomechanics through the development of improved instrumentation, experimental protocols and computational simulation, coupled with and informed by further study of the pathology and aetiology of tennis elbow, is expected to advance knowledge in this area. The aim of the research is to make substantial progress towards a complete understanding of the causes of tennis elbow with a view to improved equipment designs.

The general objectives of the research are to:

- Develop advanced racket instrumentation techniques capable of monitoring racket and human performance
- Develop advanced biomechanical simulations of the one handed backhand to explore the stimuli and factors causing excessive or fatigue loading of the forearm musculature

1.2 Research Hypothesis and Method

The hypothesis investigated through the research presented here can be stated as follows:

> *Through the use of non invasive instrumentation and improved player perception elicitation techniques it is possible to substantially and usefully improve the objective and subjective assessment of tennis racket performance in play to enable investigation of better design characteristics and fatigue related injury phenomena.*

This statement reflects a development of previous thinking in this field in so far as:

i. Sports equipment users perceive implement performance in relation to a conceptual framework substantially shared by other members of their demographic. Thus although perceived 'feel' is subjective its expression is systematic and relative indicators of magnitude meaningful in relation to the experience of real physical phenomena that can be modified by design change. Previous study of this conceptual framework for tennis racket performance has been elemental, and so the depth of insight gained, especially when considering the interrelationship or confusion between perceived 'feel' phenomena, has been limited.
ii. Although subjective player perception could be elicited more systematically and thoroughly, yielding greater racket design performance insight, a man made instrumentation system is still needed to make precise and objective measurements to qualify in use physical performance phenomena as a means

to assess whether specific design aspirations have been achieved and to determine the relationship between these achievements and player perception. Previous instrumentation approaches have been intrusive to play and so performance perception, the more so as more simultaneous measurements are attempted, and so have severely limited the scope and, perhaps, the general validity of subsequent findings. The ability to make multiple simultaneous measurements of racket performance phenomena in play without intrusion is fundamental to the future study of equipment related performance perception phenomena in a variety of sports as well as tennis.

iii. Superior designs are most likely to be developed when the relevant phenomena can be measured and are subsequently well understood so that design decisions can be made to accentuate or suppress particular characteristics as necessary.

Given these premises a significant contribution to knowledge in this area is presented in relation to the following research questions:

- What is the conceptual model used by players to assess and express their perception of tennis racket performance?
- Can the modern tennis racket be instrumented in an entirely un-intrusive manner so as to make possible multiple simultaneous measurements of critical performance phenomena without inhibiting prolonged real play use or compromising/biasing a players perceptions of racket behavior?
- Can subjective player perceptions be correlated to objective performance measurements to enable design optimization leading to superior rackets?
- Do the more play realistic and generally fatiguing experimental protocols enabled by less intrusive instrumentation give rise to significant different performance excitation scenarios to those produced in unfatigued play ?

The research method adopted to explore these questions comprised the following:

- Development of a systematic perception relationship model of the various aspects of tennis racket `feel` enabling the construction of superior player perception elicitation tools
- Investigation of the correlation between objective measurements of racket characteristics with perceived feel eventually enabling the development of a predictive design tool
- Improvement, implementation and evaluation of instrumentation techniques and human testing protocols to objectively study human and racket performance interaction under induced muscle and full body fatigue conditions enabling the development of smart racket technologies capable of diagnosing an increased likelihood of injury and the comparative benefits of different design solutions

In both aspects, objective performance assessment and subjective perception elicitation, the method is seen to comprise an initial phase where previously reported research is distilled into best practice in regard to the application and then where possible substantially bettered.

The second phase comprises the use of the improved techniques and knowledge in such a way as to demonstrate superior assessment of racket performance. It was anticipated that in doing so new knowledge relating to player and racket behavior, performance perception and fatigue related injury phenomena would also be generated.

1.3 Thesis Outline

The findings of this research activity are presented in the remaining chapters as follows:

Chapter 2 A review of the existing literature in areas relevant to the research, primarily instrumentation fatigue and player perception

Chapter 3	An outline of the process of developing a research support tool that models players' perceptions. The chapter discusses the development process in detail from the collection of data through interviews through to validation and presentation of the model
Chapter 4	Explanation of the development of a postal questionnaire to add a new dimension and depth to the existing model. Measures of relative importance and percentile use of vocabulary collected from nationwide distribution of the questionnaire were included to greatly widen the application opportunities for the model.
Chapter 5	Development of a wireless data logger system. The chapter explains why there is a need for such a system within the research context and goes on to describe how the device was refined over several iterations so that it could be best optimized for its specific application in tennis racket research.
Chapter 6	Development of the objective versus subjective perception test. The chapter discusses contrasting methodologies, reviews the initial pilot testing used to finalise the test protocols and evaluates their full implementation in testing.
Chapter 7	An account of the methods of analysis used to dissect the results from the perception tests. A summary of the data is presented to highlight any emerging trends.
Chapter 8	Development of a tennis specific full body fatigue protocol. The testing examines the relationship between fatigue and player performance. Analysis of the results assessed the success of the fatigue protocol and reports key findings.
Chapter 9	Discussion
Chapter 10	Recommendations for Further Work

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter presents a thorough cross referenced review of the previously published literature relevant to this thesis. Methodologies and protocols relevant to the work are identified and discussed. Previously reported data from similar or related experimental studies are presented. Weaknesses and gaps in the literature are highlighted to confirm the worth of the proposed research as a new contribution to knowledge.

The chapter begins by outlining an overview of the sport of tennis, including the rules of the game and equipment review. These elements all contribute to the racket design goals and trends.

Literature more relevant to the assessment of subjective performance is subsequently presented including a review of existing experimental protocols, any related implement performance phenomena and dimensions and the latest published methods of 'feel' mapping.

Literature concerned with objective sports implement performance assessment is reviewed including existing experimental protocols and associated implement performance phenomena. Particular instrumentation and data capture technologies are also considered.

2.2 The Game of Tennis

2.2.1 Introduction

Tennis is played by 2 (singles) or 4 (doubles) players on a court 23.77 m by 10.97 m with singles court lines marked out with a width of 8.23 m. The net, hung widthways across the middle of the court, is 1.07 m high at the posts and 0.914 m high at the centre where is should be held tightly with a strap (ITF, 2006).

The balls are required to be white or yellow in colour and have a uniform surface consisting of fabric cover. Any seams also have to be stitchless.

Balls may be pressurised or pressureless. Pressureless balls must not have greater than 1 psi (7kPa). Balls approved for play have to meet one of the specifications detailed table 2.1:

Table 2.1 ITF tennis ball specifications (ITF, 2006)

	Type 1 (Fast)	Type 2 (Medium)	Type 3 (Slow)	High Altitude
Weight (Mass)	231.975-2.095oz. (56.0-59.4g)	1.975-2.095oz. (56.0-59.4g)	1.975-2.095oz. (56.0-59.4g)	1.975-2.095oz. (56.0-59.4g)
Size	2.575-2.700ins. (6.541-6.858cm)	2.575-2.700ins. (6.541-6.858cm)	2.750-2.875ins. (6.985-7.303cm)	2.575-2.700ins. (6.541-6.858cm)
Rebound	53-58ins (135-147cm)	53-58ins. (135-147cm)	53-58ins. (135-147cm)	48-53ins. (122-135cm)
Forward Deformation	40.195-0.235ins. (0.495-0.597cm)	0.220-0.290ins. (0.559-0.737cm)	0.220-0.290ins. (0.559-0.737cm)	0.220-0.290ins. (0.559-0.737cm)
Return Deformation	40.265-0.360ins. (0.673-0.914cm)	0.315-0.425ins. (0.800-1.080cm)	0.315-0.425ins. (0.800-1.080cm)	0.315-0.425ins. (0.800-1.080cm)

The string pattern must consist of a series of crossed-strings attached to the frame and alternately interlaced where they cross. The pattern must be generally uniform and in particular not less dense in any area. The frame of the racket is not allowed to exceed 73.7 cm in overall length and 31.7 cm in overall width. The hitting surface must not exceed 39.4 cm in overall length and 29.2 cm in overall width.

The frame including the handle and the strings must be free of any device which makes it possible to change materially the shape of the racket, or to change the weight distribution in the direction of the longitudinal axis of the racket which would alter the swing moment of inertia or to change deliberately any physical property which may affect the performance of the racket during the playing of a point. No energy source that in anyway changes or affects the playing characteristics of racket may be built into or attached to a racket (ITF, 2006).

2.2.2 The Racket

Brody and a number of other authors (e.g. Brody, 1979, Brody, 1981, Hatze, 1992b, Tomosue et al., 1992, Wilson and Davis, 1995, Brody, 1997, Cross, 1997) have published widely on the physical characteristics (e.g. size, moment of inertia, centre of percussion, coefficient of restitution, mode shapes and vibration frequencies) associated with racket design characteristics and their general implications for players. General guidance on optimum racket selection is given, but little or no empirical evidence is given for the justifications made.

In 2000, Coe wrote “Many would cite the tennis racket as the ultimate example of technology outweighing the interests of Tradition in Sport”. This is a dispute that generally centres on the speed of the modern game of tennis. Table 2.2 shows how distinct the difference in racket technology is when comparing the more traditional wooden rackets with the modern day carbon fibre rackets.

Coe also states that for most tennis players who play the game recreationally there is only one characteristic which is important in their judgement of the quality of a racket and that is, how hard it enables them to hit the ball for a given amount of effort, or its ‘power’. Racket manufacturers have guided the majority of racket technology research and developments to improve this one performance characteristic, often at the expense of others.

Table 2.2 a comparison of racket technology progression (adapted from Coe, 2000)

Property/Specification	1973	1998
Material	Laminated wood	Carbon fibre composite
Weight (strung)	13 to15 oz.	7.5 to 10 oz.
Balance from butt end	12.5 to 13 inches	14.5 to 15 inches
Head size	65 to 70 sq. ins.	90 to 135 sq ins.
Length	26 to 27 inches	27 to 29 inches
Swing Weight	370 Kg/cm^2	290 to 310 Kg/cm^2
Vibration Frequency	Approx. 90 Hz	Approx. 150 to 220 Hz

Lammer and Kotze (2000) document the history of construction material and tennis racket technology starting with the very first wooden frames that replaced the gloves and bats of the early game. Although wood laminate, steel and aluminium rackets made some improvements in racket design, composite material technology can be described as “probably the greatest revolution in tennis rackets to date” (Lammer and Kotze, 2000). Composites began with epoxy and glass fibre but were soon accompanied and gradually replaced by carbon fibres. As the technology of the material increased the composites began to be made up of predominately carbon fibres, with the balance of fibre-to-matrix varying from 50:50 to 60:40 (Brody et al., 2000).

Over the years new methods of reinforcing a standard carbon fibre frame have helped to increase racket durability and strength whilst reducing weight. Modern low cost rackets are often constructed from a blend of carbon and glass fibre, whereas the more expensive will be based on a mix of moderate to high strength/stiffness carbon fibre with the addition of lower percentages of titanium, Kevlar or other reinforcing material, into the ‘lay-up’. Head’s method of producing their ‘Intellichip’ electronic dampening system rackets goes even further by introducing a layer of piezoelectric material within the construction of the throat connected to a printed circuit board embedded within the grip. As well as changing the response of the racket frame this method could perhaps be exploited to introduce inconspicuous instrumentation to enable further ‘intelligence’ to be built in.

Most often advances in racket design are reported to have made improvements to power production and reduction of vibration, generally associated with tennis elbow, although there are some examples of rackets built to other design criteria, such as control and comfort (Lammer and Kotze, 2000). Lammer and Kotze state that comfort is a very abstract concept that is still a very complex and vague area. They indicate players have their own way of describing how they perceive a racket, which makes it difficult to associate their comments with specific design parameters. To date most attempts to improve comfort have focussed on reducing vibration levels, often requiring stiffer frames which can substantially change the sound of impact. This potentially interferes with player perception and comfort although little research has been conducted in this area.

Racket Mass Characteristics

In their book, The Physics and Technology of Tennis, Brody et al (2002) talk about the mass characteristics, weight, balance and swing weight or moment of inertia of tennis rackets. The book explains that the perceived weight of the racket can feel different when held statically when compared to being swung, and different again if held statically at a different point on the racket. Weight is referred to as the amount of (vertical) force required to keep the racket at rest’. The balance point is the point about which the mass of the racket is equally distributed. The book explains that the swing weight of the racket is the measure of how much torque (twist) you must apply to the racket handle to get the racket to swing. The balance point is a close anomaly to the centre of gravity of the racket and likewise the swing weight or moment of inertia is classically referred to as the rotational equivalent of the mass of a linear system. In this particular example the book is referring to the moment of inertia about an axis located in the racket handle, as it is commonly referred to in the literature, rather than about the principle axis which is more generally considered when discussing the motion of rigid bodies.

Mitchell et al. (2000a) published research investigating the relationship between head speed and racket inertia for a tennis serve. The study utilised a CODA (Cartesian Optoelectronic Dynamic Anthropometer) and 2 dimensional video measurement techniques to give a comparison of results. The conclusions of the study indicated that a smaller moment of inertia allowed a faster swing, but warned that this may not be independent of the weight of the rackets. The authors speculated that in practice a player is unlikely to be able to achieve the same swing speeds with a heavier racket despite it having a similar moment of inertia to that of a lighter one. A further observation of the study was that two players were able to achieve maximum swing speeds with their own rackets, this was attributed potentially to the psychological effect of playing with a familiar racket, and suggests that if this is the case a revised protocol would be needed to eliminate this effect, in further testing.

Of the papers that relate to the mass characteristics of tennis rackets there are some that relate directly to ‘feel’ or perception. Beak et al. (2000), Brody (2000b), and Kawazoe (2000), have, to some extent, examined how the moment of inertia of tennis rackets relates to the ‘feel’.

Brody (2000b) identified the three principle moments of inertia of a tennis racket through the application of physics principles. The paper’s main focus is on how sensitive players are to differences in swing and polar moment of inertia. Players were asked to swing rackets with different moments of inertia and select which was the heavier feeling. The results indicated that better tennis players could distinguish between smaller differences in both swing and polar moments of inertia than non-players, but no attempt was made to try and understand how the players might describe the feel of the rackets, or which they preferred the feel of.

As with Brody’s study, Beak et al. (2000) investigated moment of inertia in relation to ‘feel’. A selection of adults and children were asked to wield rackets and perceive which they felt afforded striking a ball to a maximum distance. Participants then repeated the test whilst visually impaired. The study showed that adults apparently found it more difficult to determine swing weight when visually impaired, unlike the children whose discrimination appeared to slightly improve. Although limited the study did start to address participant preferences or perception of performance, since they were asked to perceive which racket they felt afforded striking a ball to a maximum distance. This study did not, however, allow participants to utilise their own vocabulary, potentially leading to misinterpretations, and only addressed one characteristic of a tennis racket, making it difficult to assess what other factors might influence perception. Furthermore, no objective measures were used, so, for example, the perception of which racket afforded striking a ball a maximum distance, was never compared to actual performance, limiting the conclusions that may be drawn from the study.

Kawazoe (2000) focused on shock vibrations from the tennis racket, based on the assumption that 'feel' is strongly associated with this characteristic. Although there was no participant feedback, the paper recognises that there is a mathematical relationship between the moment of inertia of a racket and its acceleration, and thus can affect the vibrations and 'feel' of the racket.

A similar study by Kreifeldt (2001) was published a year later. This study was not well documented failing to include basic details such as sample size and was not well related to actual tennis play, participants having been asked to swing 'baton like' objects and envisage they were tennis rackets. The study does, however, tie together Brody and Beaks studies in as far as both the player's ability to distinguish between moments of inertia and player's preferred racket choice are incorporated.

Racket Motion

Several biomechanical studies describing the kinematics of different tennis strokes have been reported (McLaughlin and Miller, 1980, Elliott et al., 1986; Hatze, 1992b, Roetert et al., 1995) Measurement inaccuracy has typically prevented the derivation of joint forces and torques. Hatze derived some personal renown from his complex analytical models of the racket and his development of a mechanical arm to simulate and so study ball/racket arm interaction (e.g. Hatze, 1992a). However, the complexity of his models, analytical and physical, makes them difficult to validate/calibrate in relation to real human performance. McLaughlin & Miller (1980) developed a simpler analytical model of forces prior to impact, but not during or after.

A number of researchers have also studied muscle group activation during tennis strokes (e.g. McLaughlin and Miller, 1980; Buckley and Kerwin, 1988; Knudson and Blackwell, 2000) Data is reported for the timing and severity of contraction, although the correlation between signal strength, the force generated by the muscle and the load it experiences presents some difficulties. Distinguishing the behaviour of a single muscle from those around it is also problematic without invasive measures.

In addition to the movement the racket undergoes as a result of the swing, the frame itself experiences movement. During impact the ball, racket frame and strings all move and deform. The duration of impact is typically 4 ms; in this time the ball compresses to around 50% of its original size and the strings and racket frame store potential energy as they deflect. The ball and strings both return to their original state, returning much of the stored potential energy to the ball in the form of kinetic energy. The frame only returns to its original state quickly enough to return energy to the ball if impact occurs in the appropriate location, in the majority of cases impact occurs elsewhere and the energy contributes to the continuation of frame movement in the form of vibration. Impact towards the tip of the racket head causes the frame to curve away where as an impact in the middle of the frame results in the frame curve inwards towards the ball. Very little movement of the frame occurs if the impact location is midway between the middle and tip of the frame, it is this point at which the most amount of energy is returned to the ball and the least amount of subsequent vibration evident (Brody et al. 2002) (fig. 2.1).

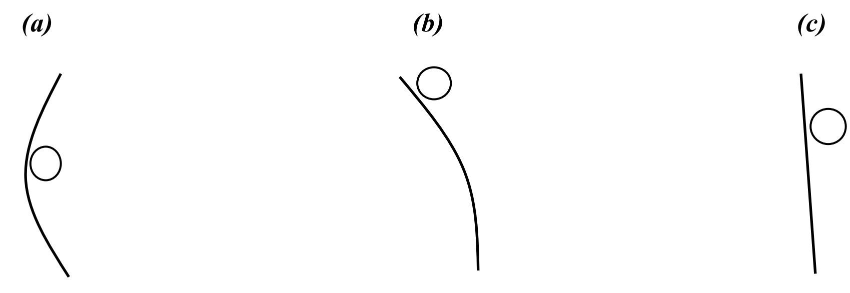


Figure 2.1 Racket frame movement for an impact at the centre (a), tip (b) and midway between the centre and tip of the frame (c) (Brody et al. 2002)

Injury (tennis elbow)

Carroll (1981), investigated the effect of tennis racket vibration on tennis elbow sufferers, testing 42 participants in two sample groups over two tennis seasons. Pilot studies indicated that, of seven rackets, the graphite injection moulded (GIM) rackets appeared to improve symptoms of tennis elbow for the majority of the participants in the sample. Testing the vibration characteristics of the seven rackets with the use of an accelerometer showed that the GIM rackets generally had the lowest amplitude vibration cycles and the highest damping factor. Testing was conducted with one group of 22 players over two seasons with the GIM rackets to investigate their effects on tennis elbow. Carroll relied on what appear to be semi-structured conversational interviews to obtain data from the tests. Of the 22 participants, 19 reported 'considerable improvement' after the first period, and of those, 8 reported 'almost cured' by the end of the second season. The second sample group was said to confirm the findings of the first, but the results were not published. Carroll concluded that it was likely that the perceived improvements in tennis elbow were due to the superior damping qualities of the GIM racket, although admitted that there maybe other contributing factors. Carroll utilised player feedback and obtained objective data on the vibration characteristics of the tennis rackets. Since they were obtained at different times in different ways, there was no way to directly compare between the two sets of data, and no 'in play' objective data. Furthermore the study relied on feedback from interview to establish the extent of recovery or pain, whereas it might have proved more conclusive with some medical or physiological measure to reinforce the qualitative data that may be subject to some form of placebo effect for example. The study is one of the first, although not specifically linked, to successfully combine both objective laboratory tests and some degree of subjective player assessment, which Carroll suggests gives "a more realistic assessment and explanation of the problem".

In 2000, Roussopoulos and Cooke completed a feasibility study for research to establish any relationship between racket design and arm injuries. They established that there were many studies relating to the symptoms of injuries such as tennis elbow and relating to ball-racket and racket-arm interactions, but at no stage had any research established a definitive cause of tennis elbow. Succeeding the feasibility study Cooke, Roussopoulos *et al*. (2002) set out to fill some gaps in the knowledge relating to the causes of tennis elbow. Cooke found in the literature that there were potentially four mechanical aspects of tennis that might be responsible for tennis elbow injuries:

i. Impulsive displacement
ii. Rotation twisting the racket handle about a normal axis
iii. Rotation twisting the handle about a longitudinal axis
iv. Transient vibrations

Based on a review of the literature Cooke concluded that the second aspect listed, 'rotation twisting the racket handle about a normal axis', was probably negligible due to the tiny displacements involved, where as the impulses associated with (i) and (iii) and the vibrations identified in (iv) were all potential contributing causes. Cooke noted a trend reported in the literature of increasing cases of tennis elbow. This encouraged anecdotal evidence that new racket technology and materials might, at least in part, be responsible for tennis elbow injuries. The suggestion is posed that the lighter rackets might allow more shots to be played with more wrist snap, a characteristic suggested by Speed (2000) in a personal correspondence with Cooke to give tennis elbow pain. Also suggested is that the newer rackets have worse damping qualities or that the larger heads allows more off-centre hits than the older style rackets.

Nallakatla *et al.* (1995), suggested a new racket grip design to help reduce peak impulses imparted to the player. The new design involved a grip which was effectively a cuff around the handle of the racket set such that a particular torsion is required to twist the cuff against friction. Thus if a torque above desirable levels is experienced, perhaps due to an off-centre hit, the racket would rotate in the cuff rather than jar the hand. The paper is an interesting new concept in an area of the tennis racket design that is often overlooked, but does not go into details of the success of the new design in play or how it affects the comfort or 'feel' of the racket or indeed its effect on tennis elbow.

Knudson and Blackwell (1997), produced a paper on the upper extremity kinematics of the one-handed backhand drive with and without tennis elbow. The study examined the techniques of tennis players of various levels of experience against the techniques of those with tennis elbow utilising a combination of strain gauges, an accelerometer and electrogoniometers. The results demonstrated that tennis elbow sufferers seemed to have similarly correct techniques to all the other participants at the elbow. More telling was the diagnoses at the wrist, which showed that tennis elbow suffers tended to 'break' the wrist by eccentric contraction of the wrist extensors after impact, unlike the other participants who continued to concentrically contract the wrist extensor muscles post impact. What was unclear was whether the difference in technique was a cause of tennis elbow or the result of it. The participants were not interviewed, for example, to discover whether the difference in technique was a conscious decision to reduce the pain experienced during the shot.

2.3 Subjective Performance Assessment

2.3.1 Experimental Protocols and Methodologies

Scanlan et al. (1988a), Roberts (2001, 2002) and Davies (2003), all utilised participant feedback to obtain data regarding perceived sports equipment performance. These studies in particular conducted conversational or semi-structured interviews in accordance with techniques described by Patton (1990, 1980). Scanlan et al. (1988a) used guided interviews to establish themes and interdependencies of what contributed to elite figure skaters success and sources of enjoyment. Patton describes the general interview guide approach as "…outlining a set of issues that are to be explored with each respondent before interviewing begins…The interview guide simply serves as a basic checklist during the interview to make sure that all relevant topics are covered…no set of standardized questions are written in advance…The interviewer is thus required to adapt both the wording and the sequence of questions to specific respondents in the context of the actual interview".

Roberts (2001, 2002) and Davies (2003), produced work based on a similar theme, creating interdependency models of vocabulary used to describe aspects of 'feel' of their respective target sports equipment i.e. golf clubs and tennis balls. The interview technique used was a hybrid of the general interview guide approach and standardised open-ended interview becoming more structured at the close of the interview. The standardised open-ended interview was described by Patton (1990) as "…a set of questions carefully worded and arranged with the intention of taking each respondent through the same sequence…(of questions) with essentially the same word…Flexibility in probing is more or less limited depending on the nature of the interview and the skills of the interviewers.”

The method of creating a hybrid interview was suggested by Patton (1990), with the explanation that in some cases, it is potentially beneficial to leave structured questioning until later in the interview to avoid losing the interest of the interviewee early on.

Scanlan et al. (1988) used Patton’s interview guide approach to investigate former elite figure skaters’ attitudes to competition. Interviews were conducted with 15 male and 11 female elite skaters which each lasted an average of 2.5 hours. The interviews were conducted in great depth and detail and in their own terms in a familiar environment. Questioning began open ended and became increasingly closed as the interview progressed, with probes applied to responses of particular interest. Interviewers were extensively trained before conducting any interviews. Participants were instructed to take their time when recalling information and say they were unable to remember rather than guess. The resulting interview transcripts ran to over 1000 pages. The number of subjects, interview length and context suggest a baseline for best practice.

The content of the transcripts underwent a process called clustering. Scanlan et al. explain “clustering involves comparing and contrasting each quote with all the other quotes and emergent themes to unite quotes with similar meaning and separate quotes with different meanings”. Remaining, un-clustered quotes were assessed for relevance and discarded if undistinguishable. An inductive analysis was then performed on the clustered quotes which identified emergent categories or ‘base themes’ in the data. By repeating the process, progressively higher level themes were identified. This continued until a level was reached where no further themes could be identified and these themes were referred to as ‘general dimensions’. A structured tree diagram was constructed from the results.

Investigations of human perception in relation to the tennis racket have also been conducted using more structured forms of feedback (Beak, 2000, Brody, 2000, Stroede 1999).

Beak et al. presented players with 6 rackets of varying moments of inertia, in blind and sighted conditions. The players were asked which racket they felt would allow them to strike a sponge ball the maximum distance. In essence the players were asked which racket felt most powerful, and this perception of power related to a preference of moment of inertia.

Brody used a procedure similar to a pair-wise comparison whereby players were presented with a pair of rackets and asked which felt 'heavier' in their hands to swing. Each pair of rackets represented a difference of swing weight of 1.2, 2.5, 5 and 10%. Participants in this study were asked more directly about their perception of swing weight, although some attempt was made to use language believed by the author to be more simply understood. Both Beak et al. and Brody have used an essentially binary feedback method in which participants rate a comparison as higher or lower. Stroede et al. (1999) asked the participant to assess the perceived discomfort of a tennis ball on racket impact on a 12.7 cm horizontal visual analogue scale ranging from 'comfortable on impact' to 'uncomfortable on impact'. The distance between the participants' vertical mark and the left hand of the scale was measured and was assigned a scaled value between 0 and 100, with 100 being the most uncomfortable. This method allowed the scale of the difference between two entities to be established, rather than merely which was higher or lower rated. Although the scale asked the participant to rate according to comfort, the physical measures taken alongside this perception data measured the vibration in the racket. In effect Stroede et al. (1999) attempted to find a relationship between perceived comfort and vibration.

2.3.2 Phenomena

Numerous experimental studies have been published that relate to perception or feel, and of those a number are specifically linked to tennis (Carello et al. 1999; Stroede et al. 1999; Beak et al. 2000; Brody 2000b; Kawazoe 2000; Haake and Goodwill 2002; Maeda and Okauchi 2002; Davies 2003), however, of those specifically concerned with the tennis racket, all focus on either physical objective measures or investigate feel with respect to one physical attribute of the tennis racket. None of them utilise a comprehensive interview to establish the factors that contribute to the players perception of the overall racket ‘feel’.

Carello et al. (1999) have shown that participants were able to haptically locate the centre of percussion, the sweet spot, of a racket or bat through wielding alone. 7 unskilled participants were recruited to make up a ‘novice’ sample group. A further 7 varsity tennis players and a coach made up the ‘skilled’ sample group. An opaque curtain was used to obscure the participants view of the racket and playing arm. Players were free to wield the racket for as long as was needed. Carrello et al. (1999) observed a systematic error for both sample groups when judging both racket length and racket sweet spot location. The reliability of the measures from each participant ranged from 3.3 to 10.6% deviation for sweet spot location judgements and ranged from 3.0 to 8.1% for judgements of length. The repeatability of these measures suggests that both novice and expert participants seem to be able to determine information about the location of a rackets sweet spot simply by wielding. It also seems that wielding a racket can provide two distinct perceptions of distance from the hand. Similar findings are reported when the experiment was repeated with the racket replaced with a weighted rod.

In a related paper, Beak et al. (2000) demonstrated that a sample of inexperienced children and adults and experienced adults were able to detect small changes in inertia (~4%). 3 groups, each consisting of 10 participants, were recruited; an inexperienced child group with a mean age of 10 years, an inexperienced adult group with a mean age of 28 years and an experienced adult group with a mean age of 22 years. 6 identical racket frames were weighted equally with varying mass distribution to change the moment of inertia of each. Black tape was used to conceal the additional weight from the participants. The flat, or stroke, moments of inertia of the rackets ranged from 0.0334 kgm^2 to 0.0512 kgm^2 about the racket butt.

Participants wielded the rackets for approximately 10 minutes under two randomly ordered conditions, visual and non-visual. In the visual conditions the participant was required to wield each of the 6 rackets separately. The participant was asked to judge which 3 rackets would allow them to hit a sponge ball the furthest distance. The non-visual condition was similar to the first but in this case the participant was required to wield the rackets through a window in a screen with a sheet to occlude the participant's vision of each racket. The test was then repeated over a 1 week period.

The results of the study showed that all three groups were sensitive to small changes in moment of inertia (~4%). The children demonstrated less variability in their choices when their vision was occluded in contrast to the experienced adults that demonstrated slightly more variability. All the groups consistently selected rackets that yielded the same degree of variability indicating that their perceived choices were not randomly selected.

A 4% change in moment of inertia is more sensitive than that predicted by the Webber-Fechner or Webber's law (Fechner, 1860). Kreifeldt and Chaung (1979) agreed that Webber's law didn't hold for perceptions of moment of inertia but reported that inexperienced participants were unable to differentiate a change in inertia of less than 24%.

Other publications have suggested that in some cases participants may be able to differentiate much smaller changes in moment of inertia. For Example Brody (2000a) suggested that experienced tennis players' perceptions may be able to differentiate an even finer scale of around 2.5% change in swing weight inertia. Sample groups of 10, 10, 13 and 11 participants were used to examine 10%, 3%, 2.5% and 1.2% changes in moment of inertia respectively. The moment of inertia was calculated, in keeping with the literature (Kreifeldt and Chuang, 1979), about an axis in the plane of the racket, perpendicular to the shaft, passing through the handle 7.62 cm from the butt end. Lead tape was added to adjust the inertia of two identical racket frames. To attempt to conceal where the lead tape was positioned, some similarly coloured tape was also added at three alternative locations.

The players were presented with the pair of rackets and asked which felt 'heavier' in their hands when they swung it. After each series of tests the rackets were rebalanced ready for the next comparison.

The players were able to distinguish between a 5 or 10% difference in moment of inertia 90% of the time. A 5% change was detected more than 50% of the time and only 25% of the players incorrectly identifying the 'heavier' racket with the rest unable to distinguish the difference. It is worth noting that 4 players (36%) were able to correctly identify the heavier racket when only a 1.2% change in moment of inertia was present, 4 players (36%) also incorrectly identified the 'heavier' racket and the remaining 3 players (27%) were unable to distinguish a difference.

A second similar test was conducted examining polar moment of inertia (i.e. about the racket's axis of symmetry) comparisons. With a 10% difference, most experienced tennis players were able to correctly distinguish the difference in polar moment of inertia. With a 5% difference only 46% of experienced player were able to distinguish the difference correctly, with 31% incorrect, and 23% unable to distinguish. Brody explains that whilst it may appear that players are more sensitive to swing weight differences than to polar moment differences, on an absolute basis the polar moment is an order of magnitude smaller, and thus players are actually more sensitive to these changes.

Brody concludes that people that are not tennis players can only distinguish between differences in moment of inertia if they exceed 25%. Good players can distinguish a difference of only 2.5%. The results could also be interpreted to insinuate that elite level players might be able to distinguish even smaller differences. However, Brody does not comment on the statistical significance of his findings and this should cast a doubt on such an extrapolation.

Brody (2000) uses a binary method of assessing player perception asking participants to rate rackets as either heavier or lighter. Although simple and easy to understand, the participant is unable to provide any feedback on the magnitude of the difference between rackets. Other methods of assessing player perception have been published in the literature that allow the magnitude to be expressed.

Stroede et al. (1999) examined the relationship between the use of string dampeners and user perception of comfort. The test sample was made up of 20 tennis players, 10 male, 10 female of varying a levels of tennis experience ranging from no tournament experience to junior college competition. 4 of the participants were left handed and the age ranges from 18-29 years, the mean age being 20.6 ±2.5 years.

A lobster brand pneumatic tennis ball machine was used to feed tennis balls at a stationary racket held by each participant. The mean ball speed was measured using a precision radar gun and found to be 21 ±1 ms^{-1} (i.e. representative of moderately paced baseline drives of skilled club level and collegiate tennis players). Participants held the racket in front of the ball machine projection tube. Although grip pressure was not controlled, the players were asked to allow the racket to recoil naturally whilst holding it to encourage them to have a natural and comfortable grip.

2 different rackets were used for the study with and without a string dampener and two impact locations were examined. One of the rackets was a conventional, well used frame (Wilson Graphite Comp 110), the other had a wide body frame equipped with a elastometric handle system designed to suppress racket vibration (Dunlop Super Revelation Oversize). One of the impact locations was at the geometric centre of the racket and the other at the top end of the string bed.

10 impacts were conducted for each participant, so that all eight impact conditions would be tested and two additional consistency tests to assess the repeatability of the discomfort ratings. During each impact the racket face was obscured from the participants view by drawing a curtain and sound reducing earphones provided to prevent them from seeing or hearing when a string dampener was in place. Immediately after each impact the participant was asked to assess the perceived discomfort on a 12.7 cm horizontal visual analogue scale ranging from ‘comfortable on impact’ to ‘uncomfortable on impact’. The distance between the participants’ vertical mark and the left hand of the scale was measured and was assigned a scaled value between 0 and 100, with 100 being the most uncomfortable.

Pennwalt ACH-01 accelerometers were taped normal to the racket face at the handle near the index finger to produce vibration traces that demonstrated the effectiveness of the string vibration dampers and sampled at 16.67 kHz. It is important to note that the vibration traces were not recorded while the participants assessed the impact, rather collected for separate impacts performed under the same conditions. Stroede et al. claim this was done so as not to interfere with the participants' perception assessment procedure.

A relatively large 26% standard error was reported for the measurement of the visual analogue scale. The means of the two sets of repeated scores were not significantly different ($P = 0.66$). Stroede et al. explain that the visual analogue scale was used because of its superior sensitivity compared with descriptive or categorical scales. This is likely to have contributed to the measurement error magnitude.

Comparison between the damped and undamped impact traces reveals higher frequency string vibration attenuation in the damped trace, indicating that string dampers are effective at absorbing high frequency vibration. However, neither string damping nor racket type is reported to have a significant effect on discomfort ratings. Conversely impact location is reported to have had a statistically significant effect on discomfort ratings. Stroede et al. explain that the findings of the research did not support the claim that string dampers reduce impact discomfort. 13 of the 20 participants used some type of string dampener, so it seems that if hand-arm discomfort is not affected there may be some other component to overall comfort. It was suggested that auditory effects might play a significant role in overall impact discomfort. Obviously in this study participants were subject to auditory deprivation and a follow-up study is suggested to investigate more fully.

Stroede et al. considered it noteworthy to highlight the fact that, despite being of different design and manufacturer, there were no significant differences in perceived comfort levels between racket types. Although the rackets had different characteristics such as stiffness, both rackets were constructed from carbon fibre. The authors warn that generalisation of these results should be made with caution.

Comparing the vibration traces from the two impact locations shows how the centre impact results in much quicker vibration damping than for the end impact. This was consistent with the finding that players experienced more discomfort with the end impacts. Stroede et al. speculated that frame vibration is the dominant source of hand arm impact discomfort based on the fact that the sample showed no difference in comparison of perceived comfort with or without a string damper and the evidence of the spectral analyses.

Stroede et al. (1999) examined the effect of string dampers on comfort by measuring perceived comfort and vibration, which in effect examines the relationship between the two entities. Mead and Drowatzky (1997) specifically examined the relationship and interdependency of audition and vision in a separate perception study. To do this they used a sample of 26 tennis players, 14 experienced and 12 inexperienced, where players were considered experienced if they had played tennis for more than 2 years.

Participants were presented with one of three stimuli; a ball hit from the forehand side between 11 and 15ms^{-1} to 1 of 3 areas of the court. Ball speed was measured using a Sports Radar Gun. The areas were defined by three adjacent 2.7 by 5.5m taped areas between the service line and baseline inside of the singles sidelines. Balls were fed into each of the 3 areas 3 times in a predetermined counter balanced order.

The time from when stimulus commenced until subject responded was measured. Instrumentation on the racket in the form of a 5 by 6 cm aluminium board completed the circuit to initiate a timer subsequently stopped when the participant removed their foot from a sensor placed on the court.

The test was conducted twice; once under auditory deprivation, and once without any restrictions. Auditory deprivation was achieved by equipping the participants with 30dB reduction sound protectors and 27 dB reduction ear plugs.

Mead and Drowatzky report that there was no significant two way interaction for experience and location and no main effect for experience. No main effects were observed between auditory conditions for the forehand or the back hand; however, a ball fed directly showed significantly slowed reaction times when hearing was deprived. Mead and Drowatzky suggested that an interdependence between sensory modalities for tennis play may be a rapidly learned element that occurs during the initial stages of learning. This was based on the finding that inexperienced players' reaction times were adversely affected by the hearing deprivation when the tennis ball was hit directly at them, as was the case with the experienced sample. This supporting evidence relies on the assumption that inter-sensory facilitation would most likely not occur without an interdependence between vision and audition. It is perhaps questionable to consider the relationship investigated in this work as an ‘interdependence’ since vision and audition are not necessarily shown to be dependent on each other, rather that they both contribute to more effective response times. The goals and procedures presented remain relevant, even if the application is not quite as useful.

2.3.3 Feel Perception Elicitation and Modelling

Several researchers have contributed to the development of systematic techniques for eliciting and subsequently modelling a conceptual model for implement ‘feel’ from their users (Mead and Drowatzky 1997, Carello et al. 1999, Stroede. et al. 1999, Beak et al. 2000, Brody 2000b, Kawazoe 2000, Roberts et al. 2001, Goodwill et al. 2002, Maeda and Okauchi 2002, Davies et al. 2003).

Work relating to golf club development by Roberts (2002) utilised a semi-structured guided interview technique and established ten dimensions of a golf shot for drivers, in addition to fifteen themes which suggested there were relationships between the dimensions. The study aimed to develop a formalised qualitative approach for the elicitation of elite sports performers perceptions of equipment used during play. The results led to the development of a new technique, termed ‘structured relationship modelling’ by Roberts, to encapsulate and present the research findings.

The study was conducted with a sample of 15 elite golfers with a mean age of 38 ±10 years that had been playing for an average of 19 ±11 years. Roberts reported that a ‘saturation’ stage was reached where no new information appeared to be emerging after interviewing 15 participants and thus the interview programme was terminated.

Roberts adopted a ‘discovery orientated’ approach to the interview technique which imposed little restraint on the participant and allowed the characteristics important to the golfer to be identified. An interview guide was developed that outlined areas to be explored, but allowed opportunities for probing that allowed responses to be explored in the interests of completeness and depth of understanding. The guide also provided continuity and comparability between interviews.

A variety of clubs and balls were provided that were believed to encompass the spectrum of feel characteristics associated with golf equipment. The golfer was introduced to the interview with a pre-prepared statement encouraging them to comment upon the 'feel' of the club-ball combination they've used. Questions were open ended, with clarification and elaboration probes used to obtain detailed descriptions and a more comprehensive understanding.

The interviews were recorded using lapel microphones that fed into a transmitter. Separate microphones and transmitters for interviewer and participant were recorded on separate tracks of a stereo recording device. In the event of talking over each other, the tracks could then be separated and data loss avoided.

An inductive approach was used to structure the raw data into meaningful themes, allowing themes and categories to emerge from the quotes. Unambiguous questions were used that did not guide or force responses in a particular way to minimise the sources of error reported by Cohen and Manion (1980):

- The attitudes and opinions of the interviewer
- A tendency for the interviewer to see the respondent in his own image
- A tendency for the interviewer to seek answers that support preconceived notions
- The interviewer misinterprets the responses
- The respondent misunderstands what is begin asked

The analysed data was validated by repeating the interview tests with a sample of 5 elite American golfers. Roberts warns that "although it was encouraging that no additional themes emerged, a study with a larger sample of American golfers would be required to confirm that the results of this study are applicable to a similar group of American golfers".

A taxonomy of general dimensions and related entities was created from the inductive analysis. Ten general dimensions emerged from the golfers' responses (Roberts, 2002):

i. Feel from impact
ii. Impact sound
iii. Shaft feel
iv. Club weight
v. Club control
vi. Feel of club position during swing
vii. Grip
viii. Ball flight
ix. Club appearance
x. Golfers' psychology

Roberts summarised these dimensions with a selection of sample interview quotes. Quotes made up of statements that could be coded into several different categories were kept whole to maintain the meaning. These types of statements commonly indicated an inter-dimension relationship that could not be represented by the simple taxonomies used previously. A relationship map was created to account for these additional inter-dimensional links.

Roberts notes that manufacturers of golf products need to assess aspects of their equipment other than distance or power achieved. Although only a few golfers described inter-dimensional links, they are suggested to exist. Roberts stated that the emergence of these relationships warrants further work to investigate the nature and relative importance of each. He suggested that this method of mapping could be used to develop improved investigative instruments such as questionnaires and that the method could be applied to any player evaluation of equipment, but that this presents some difficulty with dynamic games such as tennis or squash.

Roberts (2002) also explained how the use of a postal questionnaire can resolve the issue of relative importance and affirm the emergent relationships evident in the feel map. The same recruitment criteria were maintained for a further group of participants but a much larger sample was targeted, 300 questionnaires were distributed with an expected return rate of 25%, with a goal to receive a minimum of 75 completed questionnaires.

A nine point scale was used to quantify golfers 'ideal' feel in the first section of the questionnaire. Where possible descriptive words or phrases used by the golfers were taken from the interview testing, for example, in reference to the question "How quickly would you feel the ball to have come off the come face?" the word 'lively' and the phrase 'ball comes off quickly' were used to describe the most positive end of the response scale.

Seven characteristics were prioritised as areas of particular interest for the next section of the questionnaire used to investigate relative importance:

i. Shaft flexibility
ii. Club weight
iii. Grip
iv. Flight trajectory
v. Distance
vi. Accuracy
vii. Control of flight shape
viii. Club appearance

Once again a 9 point scale was used similar to that in the 'ideal' feel section of the questionnaire. In this instance the questions were labelled with the orientation phrases, "not at all important", "moderately important" and "extremely important" rather than using descriptor from the interview analysis.

81 completed questionnaire were received and analysed. Analysis of the responses produced a mean rating for each of the 'ideal' feel questions. In general 60-90% of the sample agreed what the ideal feel should be for a given characteristic, with the exception of "how would the impact feel in your hands?" suggested that ideal feel for this characteristic is more specific to the player. Roberts also warned that the mid range rating of impact sound might have been influenced by his use of descriptors 'dull' and 'tinny' for his range extremes since both can both be considered undesirable sound qualities.

The relative importance of each characteristic was grouped into one of the following categories:

i. Outcome variables which cover characteristics that are the result of an impact.
ii. Variables that have a direct effect on the outcome, e.g. grip, shaft, weight.

iii. Characteristics that do not have a direct effect on the result of the shot but can influence the players' perception of the quality of the shot and the equipment.

Analysis of the results produced an order of importance for all the characteristics. The three highest ranked characteristics belonged to the outcome variables group suggesting that any design changes to adjust for 'feel' should not be done at the expense of performance. It is worth noting however, that when the mode of the responses is considered that 11 of the 15 characteristics questioned had the top 9 rating making it difficult to clearly distinguish between each.

Roberts (2002) used the results from this work to investigate the relationship between objective and subjective data. Participants were to be questioned about their perception of objectively measured shots, and a comparison made between the two measures. The problem with questions used in the postal questionnaire is that initially golfers will not have a common reference level potentially resulting in each individual using a different range within the overall scale. Although alternative 9 point scaling methods were considered each had its own more prominent faults. Roberts resolved to use the original question format and to develop techniques to overcome its limitations. It was expected that after a few shots with the first club that the golfers would develop their own reference level to work from. As a result the biggest errors were expected to occur with the first club, so a decision was taken to remove this first club from the analysis of every player.

A selection of 5 feel characteristics, one of which would be an overall feeling of pleasantness rating, were chosen to be used in the objective versus subjective investigation. The 5 characteristics were selected from the original 15 based on their relevance to the objective measure and their rate of occurrence in the interview tests.

Both tactile sensation and impact sound were investigated in two separate studies, each with 5 associated 'feel' questions. Roberts remarked that much of the literature reports accelerometer mounting locations that do not coincide with the players grip location, where the player will perceive the club vibration. Some reports of accelerometers mounted on the player's knuckle, wrist and elbow (Fairley 1985, Tomosue 1991, NaB et al. 1998, Hennig at al. 1992) have also been mentioned but also deemed inappropriate for the study in question since most of the perceivable vibration is effectively damped by the human body. Roberts resorted to a method developed for industry to assess the injury potential of vibration transmitted to the users of power tools. The method involves clamping an aluminium adapter on which two accelerometers are mounted perpendicularly, which could be comfortably gripped between the hand and the golf club during play. A further two Bruel and Kjaer type 4375 accelerometers were mounted on the club shaft itself to attempt to correlate these measures with the golfers responses, with a view to removing the more uncomfortable gripped accelerometers in future tests.

The cables from each accelerometer ran along the left arm over the shoulder and down the back of each golfer. The wires were held fast with a combination of wristbands and clips. To assess the player assessment of ball speed off the club both club speed immediately before impact and the ball speed immediately after impact were measured. The club head speed was measured using light gates to trigger a digital timer and the ball speed measured using high speed video footage. Impact location was assessed by using a powder spray on the club face and measuring the location of the mark left after impact.

For the impact sound study a microphone was situation a similar distance from the ball as the approximately location of the golfers head to the ball. Some tests were also conducted with microphones attached to a baseball cap to compare the results when the measurement was taken closer to the participant’s ear. In this test the impact location was measured by applying pressure sensitive tape to the club face, which was measured at a later date.

Each study was conducted with a sample of 15 elite golfers aged between 20 and 55. No golfers participated in both sets. Each shot was rated on each of the 5 questions presented. Club order was arranged according to a Latin square arrangement to overcome ordering effects. In the vibration test the participants’ perception of sound was suppressed by ear defenders playing ‘pink noise’.

Results analysis revealed that the golfers’ use of the rating scales varied from participant to participant. To address this problem the mean and standard deviation of each participants' ratings were calculated. Their responses could then be standardised by subtracting it from the mean rating then dividing the result by the standard deviation. Thus the mean of the standardised scale was zero with a standard deviation of 1. Appropriate frequency ratings were selected to account for the non-linear response of humans to sound and vibration.

Interdependencies such as that established by Mead and Drowatzky (1997) between vision, audition and reaction time, which required a significant amount of time and resource, were derived from the interviews and indicated on Roberts model for ease of reference. However, the worth of work such as that presented by Mead and Drowatzky should not be overlooked and additional research could be conducted to add objective data to these, essentially subjectively derived, interdependency links as will be demonstrated later in this thesis.

Methods arising from Roberts research were utilised by Davies (2003) to investigate the relevant vocabulary and interdependencies between characteristics relating to the 'feel' of tennis balls. Eight dimensions emerged from the work:

i. Ball sound
ii. Feeling from impact
iii. Bounce
iv. Control
v. Appearance
vi. Wear
vii. Ball flight
viii. Player's psychology

A similar network diagram style feel map with links between dissimilar dimensions, where these were indicated by the interview statements, was constructed.

Davies (2003) also investigated the relationship between objective and subjective measures of sound and vibration using similar methods to that reported by Roberts (2002). The methods were adapted to a tennis context. For vibration measurements the accelerometers were mounted, similar to that as described by Roberts, on an adapter designed to fit between the grip and the hand of the participant. In this case the adapter was constructed from a lightweight and stiff nylon material that has a less intrusive effect on the properties of the racket and the players grip. Davies admits that this form of instrumentation is unlikely to be suitable for a game scenario where changing grip may be required and excessive sweating might become an issue. In keeping with related studies from the literature the vibration transmissibility to hand/arm was measured at the second knuckle of the hand, the wrist and the elbow.

For sound measurements a microphone was placed on a tripod 2.5m above the court close to the racket-ball impact for service, and an accelerometer mounted to the throat of the racket to provide information about the frequencies of vibration in the racket that cause sound and might influence the ball sound detected.

Davies chose to use a pair-wise comparison to compile subjective data rather than the questionnaire format used by Roberts. Players were asked to compare two ball types with questions such as; “Compared to the first ball how did the second ball feel?”. The participants were asked to respond on a 3 point scale selecting either positive, negative or neutral for each question. The results could then be used to find the players’ preferences for comparison with the associated objective measures.

2.4 Objective Performance Assessment

2.4.1 Experimental Protocols

A significant amount of research has investigated various means of surveying, monitoring and measuring athletes’ performance. Many of these publications focus on methods of recording overall game statistics (Brody 1990, Huges 1994, O’Donoghue and Ingram 2000, Pollard 1987, O’Donoghue 2001, Haake, Rose, and Kotze 2000) or of specific shot or movement statistics (Blomqvist et al. 1998, O’Donoghue et al. 1998, Hughes et al. 1989, Hughes et al. 1994, Taylor and Hughes 1998). A variety of techniques to monitor play outcome, bounce location, ball speed/ shot power and string bed impact location have been employed.

Play outcome

Some of this research has enabled some degree of play outcome prediction or simulation to be possible. Hannan (1976), adopted a mathematical approach to predicting play outcome. The research demonstrated how it was possible to mathematically calculate the probability of the success, on average, of different serving strategies in tennis based on statistical principles. Brody (1990) used a computer program to calculate the probability of a game ending with a tie break. His results indicated that the probability is greatly dependant on the relative ability of the two opponents and the court surface affect on the effectiveness of the serve. The probable outcomes predicted by the program were found to be comparable to the 1989 Wimbledon tournament result statistics. Play outcome in general has been recorded by a range of scoring systems ranging in detail.

Ball landing location

In many experiments it is necessary to use a ball machine to feed balls to a participant. Coaches often warn that players find it hard to hit from a ball machine since there is no stroke to aid anticipation of the ball. Thout et al. (1998) contradicted this by showing that a sample of experienced tennis players were able to predict the landing location of a tennis ball fired from a ball machine, more closely than when shown a live model executing a selection of tennis strokes.

It is often left to the human eye to judge the landing spot of a ball when the participant is aiming to hit a target for example. Avery et al. (1979) assessed serve accuracy by monitoring which half of the service box they landed in. Stanbridge (2003) assessed participant accuracy by marking lines across the court up to the base line, with higher accuracy scores awarded the closer the ball was hit to the base line. McCarthy (1997) and Bowyer (2003) both used quarter court 'consistency' targets and smaller 'accuracy' boxes within. McCarthy marked out 1.5 square 'accuracy' targets in each corner of the singles court, with the back edge incident on the baseline. Bowyer marked out a quarter court accuracy target with the back edge also incident on the baseline.

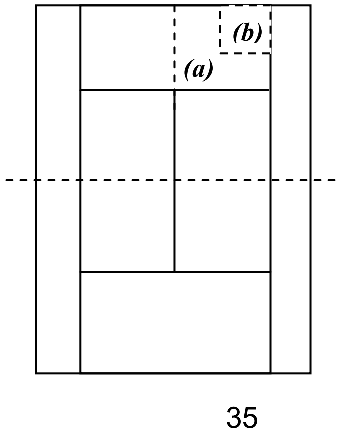


Figure 2.3 Bowyer target boxes, consitency box (a) and accuracy box (b)

Ball speed and power assessment

Power or ball speed assessment is also commonly required, often alongside ball landing location, for experimental investigation. Both Avery (1979) and Stanbridge (2003) have used ball bounce distance to assess shot power. Lines marked beyond the base line were used to judge where the ball landed after the initial bounce, with higher power scores being awarded to further bounces.

Brody (1993) developed a technique to assess approximate ball speed as it leaves the racket strings by measuring the time the ball takes to travel from racket to racket and using a conversion chart produced from a computer model. The technique relies on a number of assumptions and is essentially based on a regression from an average ball speed so may not be suitable when a more than a modest degree of accuracy is required.

Bowyer (2003) used a SpeedCheck Doppler shift radar system to measure ball speed as it crossed the net as an indicator of power. The system returned unrepresentative measures of ball speed when the ball approached at oblique angles, although this was over come by restricting the path of the ball by using consistent ball delivery and shot targets. To calibrate this system would have been time consuming, and since an absolute measure of ball speed was less important that the relative change in speed, the SpeedCheck factory settings were used. Although the absolute measures of ball speed were questionable the system did provide a repeatable measure, superior to the other methods mentioned above, allowing a comparison of ball speeds within the study.

String bed impact location

String bed impact location can have a considerable effect on the performance and feel of a tennis shot. Thus, it is sometime necessary or at least useful to be able to monitor the impact location of shots played ‘in play’. NaB et al. (1998) examined the effect of impact location on vibration and developed a method to ascertain impact location. Steel wires were woven around 14 mains and 18 cross strings to detect the electrical charge of the ball and indicate its location on the string bed. The shock and vibration transmitted to the arm was measured using an accelerometer secured to the boney protrusion on the wrist (Process Styloideus Ulnae).

Miyashita et al. (1992) mounted two strain gauges on a racket frame, one between the racket frame and the grip and the other on the frame near the top of the racket. The waves detected from impact were used to attempt to predict the impact location of the tennis ball on the racket face. The ball was projected onto 31 impact points on the racket head. Miyashita et al. claim that the mean wave height correlated well with a given impact point.

2.4.2 Racket Performance Phenomena

Impact location and the sweet spot

Maeda and Okauchi (2002) examined impact locations, and defined one location as a 'sweet' area, impact location, the definition of the 'sweet area' or 'sweet spot' has been approached by many researchers (e.g. Brody 1979, Brody 1981, Hatze 1994, Brody 1997, Cross 1997, Cross 1998, Hatze 1998, Nab et al. 1998, Carello et al. 1999; Mohanty and Rixen 2002). Brody defined three potential sweet spots on a tennis racket, the power point or region, the centre of percussion and the nodal region.

The power point is defined by Brody (1981) as the point at which the coefficient of restitution, COR, is a maximum. Howard Head often referred to the sweet spot as the region of the racket at which COR is above some arbitrary value, both Brody and Hatze (1994), were in agreement that there should be a clear and separate definition of the power point and the power region. Hatze, examined the concept of an effective power region in tennis rackets, and in the paper refers to the same three sweet spots as detailed by Brody. The study proposed that players preferred to hit in the region generally occupied by the proximally located node and centre of percussion sweets spots, and that the power spot lay outside the general hitting area. After establishing a region of the racket readily used by tennis playing participants, Hatze, suggested that an 'effective power region' would be a more useful and practical definition.

As explained by Brody (1979), when a ball impacts anywhere off the centre of mass, there is a point on the racket where the translation velocity is counterbalanced by angular velocity and so is instantaneously at rest, the area at which impact causes this point to lie under the hand is known as the centre of percussion. In Hatze's (1994) paper, Hatze stated that due to the proximity of the centre of percussion and nodal point, it was difficult to distinguish which, or what combination of each, would optimise the preferred impact location during play. In a later paper Hatze (1998) went someway towards resolving this quandary. In the course of the study Hatze developed the manusimulator, a mechano-electronic device for testing objectively the biodynamical properties of tennis rackets. From the results he established that there was no apparent stationary locus of restraint anywhere on the racket. This was attributed to the reality of the dynamics of the tennis racket design and materials, and, in the opinion of Hatze, put into question the importance of the centre of percussion as a sweet spot, suggesting that a migratory locus of restraint might be of more relevance. Cross (1998), claimed that results from his study of tennis racket sweet spots, were in agreement with Hatze, but attributed forces present at the hand during an impact at the centre of percussion to vibration, and persisted in referring to the potential sweet spot as the centre of percussion.

When a tennis racket is struck it will oscillate initiating standing waves throughout the body. The standing waves have points of maximum and minimum amplitudes known as nodes and anti-nodes; nodes in fact are points on the waves with zero amplitude. In a tennis racket the first order mode of oscillation has a node located on the string bed, and as such, if a ball were to impact at this point no first order standing wave would be established in the racket. This spot is often recognised as the true or preferred sweet spot (Hatze, H. 1994; Cross, R. 1998; Nab, D., Hennig, E. M. et al. 1998; Brody, H. 2000a) on the basis that either players have a general preference to the feel of impact in this area or that impacts here produce little or no vibration at the hand eliminating at least one of a number of potential discomforts.

Further to these three widely recognised sweet spots, Cross (1997) identified a further impact location worth noting. This spot near the racket tip is often referred to as the dead spot, and occurs at a point on the string bed where the apparent coefficient of restitution is minimal. Cross claimed, almost paradoxically, that, for shots such as the smash and serve, the highest ball speed could be achieved by striking at the dead spot. Cross justified this claim on the basis that for a racket rotating about its heel, the equivalent mass of the racket at its impact point, comes close to that of the ball, thus at impact the racket stops dead, and all momentum is transferred to the ball. This phenomenon coupled with the fact that the dead spot, being furthest away from the pivot, moves faster than any of the other ‘sweet spots’, results in the highest ball exit speed in shots utilising a wrist snap. This idea is quoted by Kotze et al. (2000) in reference to its relationship with the tennis racket’s role in the speed of tennis serves.

In his racket tests Cross used a piezoelectric accelerometer, which was effective in monitoring not only the accelerations undergone as a result of impact, but also the resulting vibration. Cross observed that the racket continued to vibrate with substantial amplitude after the initial impact. He concluded that, although the dead spot might be the best place to strike a serve or smash in terms of performance, players should be recommended to strike closer to the centre of the strings due to the potential discomfort caused by the substantial vibration after impact. Although the study completed by Cross comprehensively addresses the majority of the theory associated with the dead spot and to some extent confirms the theory with laboratory tests, the conclusions are not tested in simulated or real play situations. This may give rise to some un-addressed issues and since there was no means for player feedback gives little basis for the conclusion that striking at the dead spot would cause discomfort. It may be fair to assume that impacts off the dead spot that are unintentional may cause some discomfort, but it is less clear cut for those shots where high shock and vibration is anticipated and potentially accounted for such as in a service when player’s might alter their grip response.

Shock and vibration

Racket vibration is a factor very commonly associated with tennis elbow as well as being recognised as a factor contributing to racket feel. The importance of this issue commercially or otherwise is reflected in the depth of published experimental work (Elliott et al. 1980, Fairly 1985, Carroll 1986, Hennig et al. 1992, Tomosue et al. 1992, Jandak 1993, Kawazoe 1994, Wilson and Davis 1995, NaB et al. 1998, Cordingley 1999, Stroede et al. 1999, Wu et al. 2001, Maeda and Okauchi 2002, Brody et al. 2002)

Fairley (1985) examined vibration transmission to the hand in static gripped racket conditions. The experiments used two piezoelectric accelerometers, one attached to the racket frame near the handle, and one on the knuckle of the index finger of the participant. All frequencies of vibration up to around 100Hz were found to be transferred to the hand, with the predominant free vibration at about 100Hz, although this decayed quickly leaving the relatively un-damped higher frequencies. Fairley reported that, contrary to expectations the impulse appeared to be larger in the racket with a loose grip than with a tight one, the grip had a smaller effect on the vibration transferred to the hand, with measurements suggesting that less vibration was transmitted with a looser grip.

Hennig et al. (1992) also examined vibration mitigation through the racket to the hand and upper arm. He calculated that off centre impacts generally resulted in 3 times increased acceleration amplitude values when compared to central impacts, and suggested that oversized heads resulted in reduced vibration levels. The study also revealed that within a sample of skilled and unskilled tennis players, the skilled participants experienced lower levels of vibration. From all the results it was apparent that more than four fold reductions in vibration were found between the wrist and the elbow indicating good attenuation properties of the joints.

Jandak (1993) examined the vibration dampening properties of rackets and suggests that it is the carbon fibre composite material rather than design which gives them high internal damping, and that it would not be possible to construct a racket from these materials with a total vibration time shorter than 100 ms. Vibration dampening is reported as 2-10 times shorter when the racket is held in the hand compared to clamped conditions. The paper also indicates that grip force has a strong influence on the maximum frequency values in the range 35-75Hz.

Like Hennig et al. (1992), Kawazoe (1994) compared centre and off centre impacts. He created an impact model to predict the rebound velocity of a ball when it hit the strings of rackets with various physical properties, such as frame stiffness, mass distribution and string tension. The paper contains data on several rackets' 1st vibration mode, all of which range between 122 and 215Hz. The author explains that the model demonstrates how central impacts result in much lower amplitude of vibration than in off-centre impacts, and even less for rackets with oversized heads, contradicting in part the conclusions of Jandak (1993). Elliott and Blanksby (1980) also reported lower vibration levels in oversize rackets, but, unlike Kawazoe, indicated that these were most evident for off-centre impacts, and attributed the difference to increased polar moment of inertia. Both Kawazoe (1994) and Elliott and Blanksby (1980) reported vibration amplitudes of up to 6 mm frame deflection.

Wilson and Davis (1995) investigated shock mitigation in the tennis racket and the damping effects of grip tape and string dampers. In the first experiment a racket was clamped at the grip and hung vertically whilst a suspended tennis ball swung into the string bed. In the second experiment the racket was clamped to a force plate at the grip and stood vertically with a ball machine firing a ball at the string bed. An accelerometer was mounted at the tip of the racket to measure vibration and a high speed camcorder used to measure ball speed. The results showed that grip tape increased vibration dampening by up to 100%, which although relatively small compared with the joint attenuation reported by Hennig et al. (1992) was still a substantial contribution. The results also indicated, in agreement with the findings of Stroede et al. (1999), that a string dampener makes little difference to the vibration levels experienced by the player. The study also reports significant differences in the dampening properties of different racket materials including wood and metal, with composite rackets being the most proficient.

As reported in section 2.4.1 NaB et al. (1998) examined the effect of impact location on vibration. 19 expert tennis players performed 30 forehand and backhand straight strokes with little spin on the ball. Relationships between impact location and shock and vibration transmitted to the arm were calculated using regression analyses. The shock and vibration transmitted to the arm was measured using an accelerometer secured to the boney protrusion on the wrist (Styloideus Ulnae Process).

NaB et al. (1998) report that despite participants all being of a similar performance level the patterns of ball contacts were very different when compared between individual players. Of the players that achieved the highest ball velocities the forehand ball impacts were all located within an area approximately 6 by 7cm on the racket face. The contact areas of the forehand and backhand contacts represented less than 5% and 8% of the total racket face area. Some 'rolling' on the string bed was detected for both forehand and backhand strokes, with the ball consistently moving slightly towards the top of the racket in each case. Impacts for the forehand strokes tended to be slightly left of the racket head centre line with backhand impacts located more symmetrically around the racket head centre. Shock on the arm increases significantly with increasing longitudinal impact locations. NaB et al. claim that the minimum shock and vibration locations on the racket head identified in this study are substantially lower than those reported by Brody (1988) and centre of percussion and the racket node as summarised in table 2.3:

Table 2.3 a comparison of 'sweet spot' locations on the tennis racket (NaB et al., 1998)

	Brody, 1988	**Forehand NaB et al.**	**Backhand NaB et al.**
Point of minimum arm shock	3 mm above string centre (COP)	Shock is reduced with lower impact locations	Shock is reduced with lower impact locations
Point of minimum arm vibration	23 mm above racket head centre (Node)	18 mm below racket head centre	18 mm below racket head centre

NaB et al. go on to explain that Brody also predicted the point of maximum ball speed below the racket head centre. The data reported shows the opposite trend towards a maximum ball velocity location slightly above the racket head centre. It is speculated that mechanical coupling of the hand with the racket and the contribution of racket rotation during the swing have a substantial effect on the rackets characteristics.

Sound

In 1976 Bernstein published a paper which demonstrated how it was possible to determine the co-efficient of restitution using the noise of the collision rather than more conventional methods. The method is less time consuming, but a little less accurate than the more familiar drop test methods. Although in this case the method relies on measuring the time between impact noise, rather than an analysis of the sound itself, it does pose an interesting possibility that perceptions may be able to be link with objective measures as a means of saving the time and costs of testing.

As has been discussed earlier in the chapter Roberts (2002) and Davies (2003) examined the effect of sound on player perception in reference to golf and tennis respectively. Both methods utilised microphones positioned at the same height, the same distance from the impact location equal as the ears of the player. This method was deemed to be less imposing than mounting them above the ears on the participants head. In either instance it was not possible to control the variance in sound pitch or volume, but this presented a particularly challenging problem in tennis with the string bed tension and condition contributing to the sound of impact.

2.5 Instrumentation

2.5.1 Overview

Instrumentation can be one of the most crucial elements of experimental study, dictating what protocols are possible and which measures can be recorded. It is often the case that the instrumentation itself poses challenges and various innovations and methods of mounting, signal conditioning and application are reported in the literature (e.g. Fairly 1985, Knudson 1988, Tomosue 1992, Tomosue 1994, Brody 1995, Cross 1997, Knudson and Blackwell 1997, Maeda 2002, Mohanty 2002).

The various technologies previously used to objectively assess tennis racket performance are described in the following sections.

2.5.2 Strain Gauges

In their 1997 paper, Knudson and Blackwell, detailed the use of several forms of instrumentation to obtain data from the tennis racket. As mentioned earlier, this particular study made use of strain gauges, a low-mass accelerometer, and electrogoniometers. Strain gauges were mounted on the racket, wired, in a full-bridge configuration. Knudsen details a similar technique in his PhD thesis (1988), where strain gauges were mounted at 90º to each other, at a 45º angle to the racket very near to the racket handle, and wired into a full-bridge configuration. The full bridge allowed maximum output, strain resolution, good temperature compensation and the balancing or elimination of any sensitivity to transverse and longitudinal strain. This made representative measurements of torsion in the racket shaft possible. Maeda and Okauchi (2002), used similar instrumentation, strain gauges pasted to the racket shaft, in conjunction with accelerometers to monitor racket vibration and its transmission to the arm. A low-mass accelerometer was bolted to the throat of the racket and used to examine impact acceleration.

2.5.3 Accelerometers

Use of accelerometers in tennis racket instrumentation is relatively common with a fairly wide variety of application. In Knudson's 1988 PhD thesis, a triaxial accelerometer was piloted to examine high frequency vibrations of the racket. The accelerometer was removed for full testing since it was judged to add too much weight and wiring, which created considerable noise. More successful application of accelerometers to tennis racket vibration assessment has been documented by many authors, (Fairley 1985, Tomosue et al. 1992, Tomosue et al. 1994, Brody 1995, Cross 1997, Maeda and Okauchi 2002, Mohanty and Rixen 2002), all of whom have chosen various locations and different means of mounting accelerometers. Generally the chosen location for accelerometers on a racket has been at the racket tip (Mohanty and Rixen 2002), the racket handle (Tomosue et al. 1994, Mohanty and Rixen 2002) or at or near the throat (Fairley 1985, Brody 1995), other authors have used accelerometers mounted on the body to track the transmission of vibration to the arm (Maeda and Okauchi 2002)

Another popular use for accelerometers is to gauge the shock or force experienced by the racket or arm, (Cross 1998, NaB and Hennig 1998; Kawazoe 2000). These authors have exploited the fact that acceleration is directly proportional to force, so traces of acceleration can provide information on relative changes in force. Cross positioned his accelerometers on the inside of the racket handle so that there would be no interference of the signal from the hand contacting the piezoelectric disks. Further to their use for measuring shock forces, Cross integrated the accelerometer signals to find the velocities associated with impacts. NaB positioned the accelerometer on the wrist and utilised a technique to approximately differentiate the signal associated with shock and that associated with vibration with the use of high and low band pass filters. Kawazoe was interested in impact shock forces and vibration to create an impact model of a tennis racket, and positioned his accelerometers on the racket handle, wrist and elbow. In this way he was able to monitor the transmission of shock forces and vibration through the arm.

2.5.4 Electrogoniometers

Electrogoniometers were used in Knudson's 1997 study. Two electrogoniometers were attached to the wrist and elbow of participants. The use of the electrogoniometers meant that joint angles at the wrist and elbow could be monitored allowing some comparison of technique between participants. The arrangement of goniometers, however, did not allow the degree of wrist rotation to be monitored.

2.5.5 Other Transducers

A rather unique system provided very specific information about each individual finger by using finger nail sensors. The sensors use photodiodes and LED to determine the change in colour of the finger nail, higher forces caused more compression and thus a shift in blood flow and colour, which could be related to the applied force. By arranging these sensors in 2 dimensions the system was able to detect shear forces.

2.5.6 Motion Acquisition Systems

Several researchers have used both passive and active motion acquisition systems to analyse stroke performance. Although this area has some use in assessing player restrictions and adaptations to different rackets it is less relevant to the subject of this research thus refer to Glynn (2007) for a more comprehensive review.

By recording and digitising tennis strokes Wu et al. (2001), utilised inverse dynamics to compare ball-racket impact force of two backhand stroke techniques in a biomechanical model. The study showed that the participants using a short back swing technique had shorter contact times than the longer back swing techniques, but impulse remained the same. From this, Wu et al. concluded that a longer back swing would reduce the load on the upper extremity and may help to reduce tennis related upper extremity injuries. Although mathematically modelled using well established mathematical techniques, the results were not validated with actual measurement of impulse and the relatively small sample size left further potential for inaccuracies due to inter participant variation. Further to this the mathematical techniques employed to establish results such as ball/racket contact time were based on assumptions that might be considered to be over simplified.

Mitchell et al. (2000) published research as discussed earlier in this chapter, investigating the relationship between head speed and racket inertia for a tennis serve. The study utilised a CODA (Cartesian Optoelectronic Dynamic Anthropometer) and 2 dimensional video measurement techniques to give a comparison of results.

2.5.7 Force Films and Equivalent Instrumentation

Knudson has written a number of articles concerning grip forces in both forehand and backhand tennis strokes (Knudsen and White, 1989, Knudson 1991, 1997, 1988). The data reported are based on measurements of mean grip force at only two points on the hand/grip contact area achieved by 7-12 subjects of differing ability executing 10-30 strokes. Considerable inter- and intra-subject variability is reported, but the potential correlation between the results and variations in racket speed, impact severity or impact location was neglected.

Eggeman and Noble (1985) designed and tested a baseball grip force transducer. The transducer was built into the grip of the bat and was designed to be strong enough to maintain the bats structural integrity with altering its mass characteristics greatly. The system was wired and was another example of the use of a Wheatstone bridge arrangement like that used by Knudson (1988).

Chadwick and Nicol developed a similar system based on the Wheatstone bridge. This system, however, measured grip force on 6 sides of the cylindrical grip, thus providing more information about the location of specific location of pressure and forces. The grip was designed to 'simulate the handle of a number of devices' rather than being embedded.

2.5.8 Wireless Instrumentation

Anderson and Collins (2004) published work relating to the development of a real-time augmented feedback system for sports. The original system wired and restricted to a simulated environment in a laboratory setting. Anderson and Collins stipulate that a successful and useful augmented feedback system should address the following areas:

- The system needs to be flexible since it will need to be able to cope with a number of different data types, sample rates, bandwidths etc.
- The system must be very portable to enable the athlete to perform in their natural environment.
- The system and any wiring, sensors etc. must not interfere with the natural performance of the athlete.
- The data must be able to acquire, process and display the data required for the augmented feedback instantaneously.
- For a system to be marketed on a wide scale the system must also be a relatively low cost.

These points might not all be entirely relevant in a purely research orientated context, but it is clear that there are some common issues that should be addressed in the development of any sports related wireless data collection system. Also included in the work is a review of the commercially available telemetry-based systems. The review discusses the possibilities of including lower cost mainstream technologies such as Ultra Wide Band, IEEE 802.11, Bluetooth and Zigbee. Some of the drawbacks of the use of such technologies is the range required for sports applications and where range is adequate, the rate of data transfer and size of the transmitters.

Note the lack of entirely unobtrusive/wireless objective measurement of implement performance published for tennis particularly, but also a wired range of other sports activities.

2.6 Summary

Work that has been conducted in the area of feel and perception has tended to be fairly focused and specific, no attempt has been made to examine the vast network of interdependencies or worked towards standardising the variety of subjective player assessments. An exception to this is the works completed by Roberts (2002) and Davies (2003) in relation to golf and tennis balls respectively. These studies use a perception relationship model to map a general network of player feel. This technique pioneered by Roberts (2002) was refined by Davies (2003), but is still in its infancy.

This research aims to further progress the feel map methodology, specifically in relation to tennis rackets. The tennis ball feel model by Davies (2003) might be anticipated to share common elements with the proposed tennis racket model, since the interaction of both items is the stimulous for much of what the player perceives as the performance of either. Used in conjunction the models should compliment each other, highlighting what areas of perception are related to the racket and what to the ball, and giving a more comprehensive overview of tennis feel.

It is proposed that there is some merit in considering the two items separately and independently with a view to combining the research once the models are complete since this affords the opportunity to contrast perception responses where the ball and racket are the focus of debate. The genuine need for further consideration of potential sensory confusion might then be identified and consequently the validity of both models would be established more robustly.

To date no work has set out to standardise tennis player responses leaving questionnaires and player feedback somewhat ambiguous. Most of the interview or questionnaire related sports research has focused on player responses to predetermined questions that might be open to misinterpretation by the participants. Scanlan (1988) completed a study that compiled data from guided interviews that went some way to establishing relationships between perception and performance, but only in a general sense and did not specifically examine the use of vocabulary.

When objectively assessing equipment performance using instrumentation to observe physical phenomena, particularly in a sports context, little or no research has been conducted under ‘real play’ conditions to date. Studies that have investigated tennis play have been relatively restrictive. On the whole it has been the limitations of the instrumentation that has inhibited the player in some way. In Knudsen’s (1988) study, for example, the players were restricted by what grip they could use during the test.

Although it is apparent that there is a wealth of published research relating to relevant areas of human performance and equipment technology it is not currently sufficient to test the research hypotheses.

CHAPTER THREE

FEEL MAP DEVELOPMENT

3.1 Introduction

This chapter details the development of a tennis racket specific player perception relationship model, or 'feel map'. The initial interview tests methodologies and protocols based on those reported in the literature are described and discussed. The methods of analysis and application of the resulting data to produce the final map are also reported. A summary of the chapter is presented along with further developments planned to produce a more complete map.

As identified in Chapter 2 (Section 2.4.3), a number of authors have contributed to establishing a consistent method for developing a conceptual model of feel, particularly in relation to sports equipment (e.g. Roberts 2002, Davies 2003). The procedure is generally as follows:

i. Construction

   a) Guided interviews to establish vocabulary

   National level players and/or coaches are interviewed within a realistic play context. The interview style is open and conversational in nature with care taken to avoid leading questions. Players are presented with items of equipment and asked to describe their perceptions of the equipment characteristics and performance. The items of equipment are generally chosen to represent a wide selection of extreme characteristics, intended to stimulate responses from test participant demonstrating as wide a selection of their tennis specific vocabulary as possible.

b) Transcript analysis

Transcripts from the interviews are analysed and undergo a process called clustering, by which related vocabulary and quotes are grouped together. The groupings are collected under titles, or node classifications, that describe the listed quotes and vocabulary.

c) Structured hierarchy formation

Statement groupings (or nodes) are clustered based on their description of a common implement attributed or perceived performance phenomena. More subtle differentiation in equipment assessment and description is appreciated through sub-classification within their emerging themes. The result is a hierarchal classification of perception measures and the types of description associated with those specific to the item of equipment and sports context. This is commonly expressed in both tabular and graphical form. Use of a consistent graphical technique and systematic review of the emerging feel model helps to induce internal validity.

d) Interdependency identification

Further analysis of the nodes is undertaken to identify association or interdependency between description statements indicating apparent association between the players perception of specific phenomena. Cross linking within the hierarchal feel model is introduced to represent this associativity resulting in a 'map' of perceived feel phenomena.

ii. External Validation

a) Comparison of models for different groups

A second, equivalent model may be constructed based on interviews with a different demographic group. Comparisons between the two can be made to highlight similarities and differences. Further interpretation often leads to a clarification and external validation of the respective models. Differences may be maintained where they are justified by, for example, differences between groups such as age or culture. In fact it could be argued that it is the review and justification of both similarities and differences that builds confidence in the model rather than just the simple assumption that similar thematic structures are correct and different ones wrong.

b) External validation through explicit verification

The map gives no indication of the relative importance of equipment characteristics or the representative percentile use of vocabulary throughout the total player population. Additions to the map to address these issues and further external confirmation of the identified vocabulary can be established through the use of explicit questionnaires, involving a larger sample of the player population. A postal questionnaire is generally devised and results analysed to improve and complete the feel map.

c) Application to establish correlation between subjective perception and objective performance measures.

The model and postal questionnaire analysis are used to form standardised questionnaires to be used in testing. Results from the questionnaires are examined alongside physical measures from instrumentation mounted on the equipment. Correlations between the results enable relationships to be established between subjective and objective measures from the player and instruments respectively. The existence of such relationships generally added further credence to the identified classifications.

In the following sections the detailed implementation of the construction phase of the procedure to establish a feel model for tennis rackets is described in the following sections. The validation phase is described in detail in Chapter 4.

3.2 Guided interviews to establish vocabulary

3.2.1 Participant Selection

It is generally accepted that more experienced, higher level players can better interpret sports specific perceptions. Roberts (2002) and Davies (2003) both found that around 11 interviews tended to be fairly exhaustive and that past this, little, or no further vocabulary was discovered. Experienced players were used because it was thought that they would have a more extensive and specific vocabulary, coupled with superior proprioception.

For the purposes of developing the initial perception relationship model it was decided that the highest level participants available should be used to ensure that a full range of perceptions were investigated. It was also felt that more experienced higher level players would have a more extensive tennis specific vocabulary that would be vital to the development of a general model. Some consideration was given to whether to use level 3 coaches, national level players or a combination. It was decided that coaches, who tended to be older and more experienced, might be expected to have a more extensive knowledge of the game, but may also have out dated vocabulary or lower perception levels than players currently playing at their peak. On this basis, participants from both groups, coaches and players, were selected, subject to their availability, to cover as wide a cross section of the tennis playing population as possible and consequently both current and more traditional terminology. Participants were also selected across a relatively wide age range and from both sexes. This ensured that the widest possible vocabulary was captured from the interview tests.

In the context of the study it seemed feasible to allow both male and female participants. Both sexes would have a comparable knowledge and understanding of the tennis specific language and vocabulary. The physiological differences between men and women would not affect the outcome of the study since none of the data is dependant upon physical traits such as strength or endurance, merely the participants' abilities to perceive differences in racket characteristics.

To follow previous best practice it was decided vocabulary should be elicited from a minimum sample of 15 subjects to ensure the previously experienced saturation threshold reported in the literature was reached. To lend external validity and wider relevance to the study two subject groups, one based in the UK the other in Germany, were selected.

In the UK reaching the desired quota of subjects proved surprisingly difficult, perhaps due to the hectic competition season for aspiring UK tennis players and the timing of the study within the research programme. As a result a number of different test groups were used. Eight participants were recruited from Loughborough Universities 1st and 2nd teams, and a further 5 were interviewed courtesy of the Head UK test centre in Cheltenham. To make up the rest of the sample county tennis associations were contacted across the country. Bedfordshire proved to be particularly helpful, and arrangements were made to test a further four participants at their home courts bringing the total to 17 UK participants.

The Head UK participants were experienced coaches and Head equipment testers, players from Loughborough University were ranked in the top 200 in England or equivalent and were all students aged 18-30 and the county players from Bedfordshire were high level players aged 18-40.

In Cologne 18 players and coaches were tested, the majority were high level tennis playing students aged between 18-30, although two prolific coaches were also tested. Although previous work by Roberts (2002) utilised different sample groups, one from the USA and the other from the UK, no previous published study in the sports equipment field had attempted comparatively modelling of this nature with such a profound difference in the native language between the two subject groups. This is perhaps understandable given the limited application of these techniques so far in the sports industry and the added difficulty, but it is also surprising given the international sales aspirations of the equipment manufacturers. For example, Austria based Head tennis are particularly interested in comparing the perceptions of feel expressed by UK and German players.

3.2.2 Rackets

The interview protocol involved presenting players with rackets from a limited selection judged to have extreme characteristics. The bulk of the rackets were obtained from the Head tennis museum and from within the Loughborough University Sports Technology Research Group. Below is a list of characteristics that the rackets were assessed for:

- Flexibility: the degree of lateral frame bending in the racket for a given load
- Strings: string tension, age, type, and string pattern
- Cosmetics: colour, shape and style
- Total Length: how long or short the racket is
- Grip: length of grip, type of grip, size of grip
- Sound: sound of impact, pitch, volume and duration
- Weight: how heavy or light the racket is
- Racket Material: carbon fibre, titanium, aluminium, wood, plastic
- Head Size: head width, surface area, frame thickness
- Vibration: vibration felt due to on and off centre impacts
- Brand: make of racket, grip or string
- Age: age of racket grip or string
- Wear: condition of racket, grip or string
- Performance: power, control, manoeuvrability of racket
- Balance: head heavy/handle light, handle heavy/head light
- Moment of Inertia: manoeuvrability, stability, swing ease, swing weight

The characteristics reference list was constructed by comparing lists of tennis racket characteristics compiled by the Head research and development group and from interviews with Loughborough University 3rd team tennis players. 3rd team players were used since they were clearly experienced players but unlikely to be included in the interview test sample group. It was believed that such a consultation might have implications for the validity of the results of the interview test so using players that had assisted in this area would be unwise. 3rd team players were unlikely to be considered for the full scale interview testing, thus the available sample size for the testing would not be affected by consulting them regarding conceivable tennis racket characteristics.

The combined characteristic lists were used to create a chart linking racket characteristics with common groups, highlighting any anticipated interdependency (figure 3.1).

Primarily the players were presented rackets from eight ‘core’ rackets, but a total of 20 rackets were available to the interviewers to choose from in case a substitution was needed to progress the interview process or in the event of string or racket damage in the process of testing.

These 20 rackets were selected from a collection of almost 60 rackets. The selection was narrowed down through the compilation of a tennis racket catalogue and ranking system. All rackets were assessed using a Babolat Racket Diagnostics Centre to measure the frame flexibility, balance point, weight, string bed flexibility and moment of inertia. Rackets were grouped and ranked according to their respective properties. From the groups, a selection of rackets was chosen that typically represented each group or an extreme characteristic.

The final selection of 20 rackets was given to four tennis players of Loughborough University 3rd team or equivalent playing standard. The players were asked to run through a protocol similar to the planned full interview tests so as to assess the affect of each of the rackets characteristics on the players’ sensory perceptions. Notes from the interviews were used to establish which of the 20 rackets had the most ‘extreme’ characteristics to form the ‘core’ selection of 8 rackets. These rackets would primarily be used with rackets substituted out if there were any problems with the rackets or the ordering. Including the substitutions 11 rackets were used in total (table 3.1, figure 3.2).

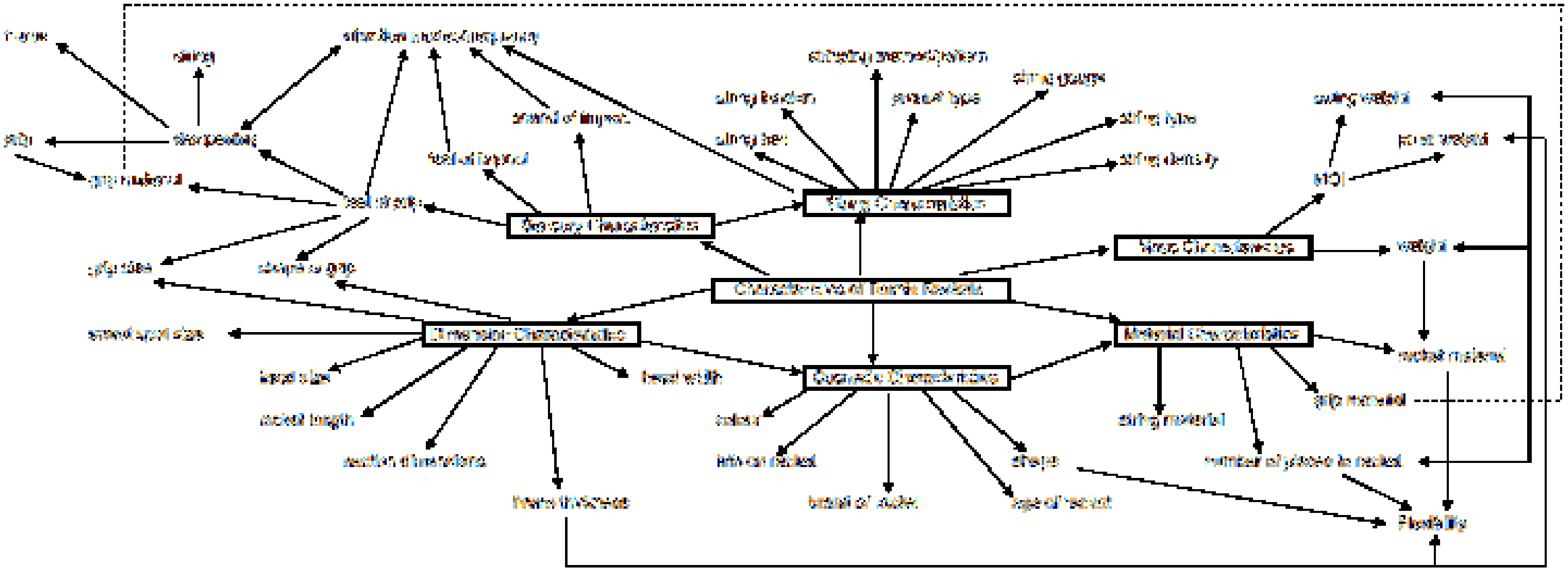


Figure 3.1 Flow diagram of racket characteristics.

Table 3.1 Measured properties of 11 selected test rackets, the 8 'core' rackets are marked in grey

Brand	Model	Colour	Weight (g)	MOI (kg/cm^2)	Weight/ MOI	Flexibility (%)	Head Width (cm)	Head Length (cm)	Head Size* (cm^2)	Length (cm)	String Bed Tension (%)	Material	Grip Type
Dunlop	Maxply fort graphite	black/ natural wood	378	344	1.10	24	22.9	28.5	512.59	68.75	19	wood/ graphite laminate	smooth wrap
Dunlop	MAX longbow	black/ red	288	385	0.75	72	28.75	41.3	932.56	72	49	premium graphite	stitched rib grip
Head	Director	metal/ orange	367	324	1.13	59	25.1	35.75	704.76	67.7	39	aluminium	PU supergrip
Head	Ti.Radical	grey/ orange	300	313	0.96	63	26	34.4	702.46	68.25	67	carbon fibre	comfortac
Head	I.X16 (working chip)	black	266	307	0.87	74	28	39.5	868.65	70.5	44	carbon fibre	comfortac
Head	I.X16 (disabled chip)	silver	266	285	0.93	69	28	39.5	868.65	70.5	48	carbon fibre	comfortac
Kuebler	Resonanz R50	white	390	364	1.07	81	27.25	36.7	785.46	68.75	50	carbon fibre	PU supergrip
Prince	Longbody, thunder superlite titanium	silver/ red	225	269	0.84	73	28.75	38.4	867.08	71.1	40	carbon fibre	PU supergrip
Prince	Long body, rip stick 800	black/ purple/ green	280	359	0.78	65	27.1	37.2	791.78	73.6	60	graphite	PU supergrip
Sports Inovations inc	G-100	black/ red/ gold	351	345	1.02	56	25.3	33.3	661.69	68.2	60	graphite fibre	smooth leather wrap (sticky)
Wilson	Sledge hammer 3.4 stretch	black/ silver	286	398	0.72	70	31.5	41.25	1020.53	73.1	50	carbon fibre	Wilson cushion-aire grip

* based on the area of an ellipse

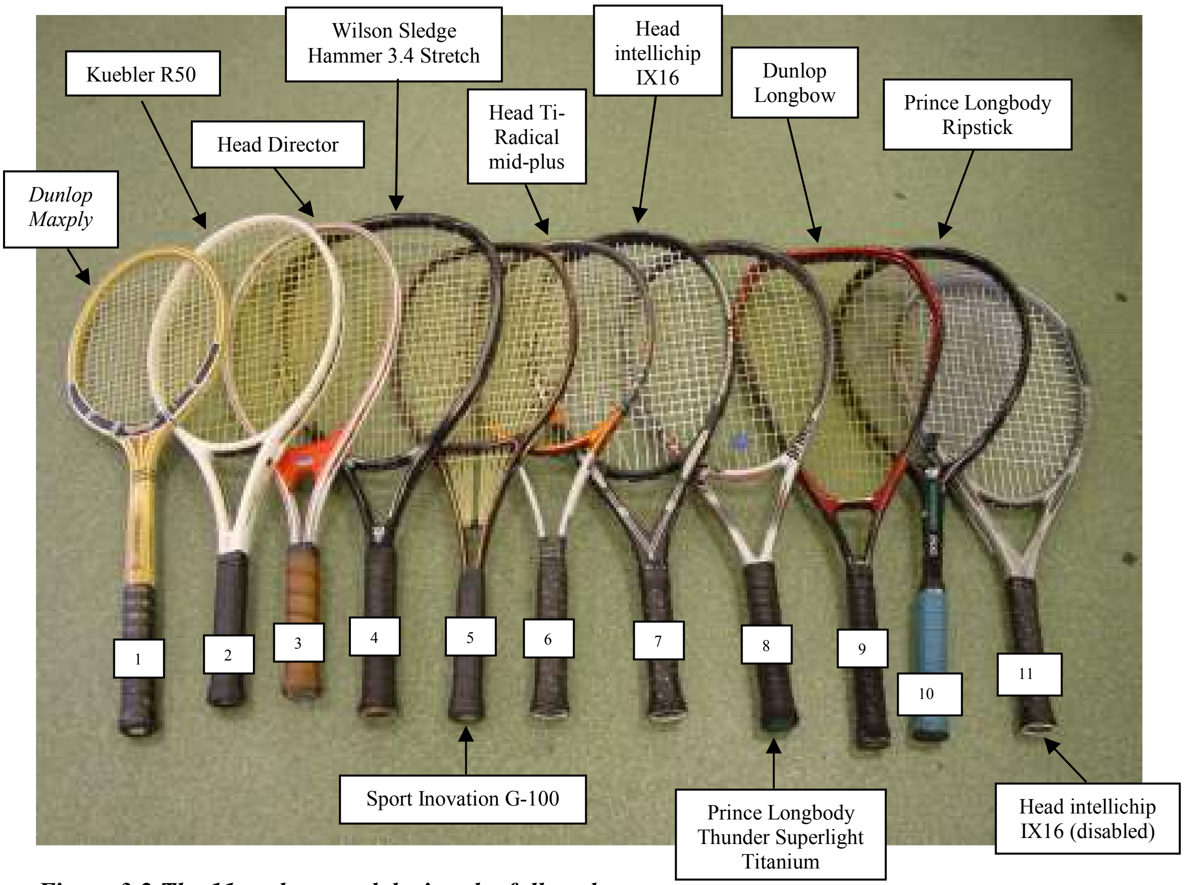


Figure 3.2 The 11 rackets used during the full study

3.2.3 Experimental Considerations

The effect of the ball was not intended to be tested in this instance. To attain some degree of control over this factor during testing newly opened Penn Pro Titanium tennis ball were used for all the tests. Additionally, where possible, tests were conducted indoors where some degree of environmental control was possible. Ideally all the tests would have been conducted this way, with the same court surface at similar times of the day to allow better comparison between groups. In practice this was not always possible; some tests had to be conducted outside, as in Cologne, Cheltenham and Berkshire and different court surfaces were encountered at each location. Since the aim of the experiment was to elicit as much descriptive vocabulary as possible, it could be argued that a wider variety of conditions would be beneficial. Whilst this is true and that the effective differences may be small, it is also worth noting that the study specifically examines vocabulary associated with perceptions of racket characteristics and not of court or ball interactions. Furthermore, with the German interviews conducted on clay courts in Cologne and most of the UK interviews conducted on indoor hard courts, with those conducted outside on asphalt, there may be implications for a comparison of the two sets of vocabulary. Although it is not possible to correct for these issues and it is possible that they may affect the degree of perception, it is unlikely that they will change entirely what the player perceives.

Over time the racket strings lost tension due to wear and in some cases broke and needed replacing. This meant the rackets used could not practically be identically strung for every test. Since the study was devised only to establish the relevant range of vocabulary used by tennis players in reference to the 'feel' of a racket. It is important that the rackets stimulate vocabulary and as such need only cover a sufficient range to represent a wide section of racket characteristics. The relevance of the racket selected, and it's stringing, is purely to most effectively elicit a full range of vocabulary from tennis playing participants. Changes in the racket selection or in the exact nature of the stringing of any of the rackets should have no adverse effect on the ultimate goal of the experiment so long as those used are sufficient to stimulate the full range of vocabulary from the players in relation to string tension.

3.2.4 Pilot Testing

The study protocol and interview techniques were pilot tested during April-May 2003. The first pilot test involved two club level players who would not be ideal subjects for the main testing, but allowed interviewers to gain experience and gave some indication of total test time. 2 interviewers were trained and given experience of interview testing before conducting full tests. A second pilot test was arranged with two Loughborough University 3rd team tennis players, to further resolve identified problems. As a whole the pilot testing helped to optimise the protocol structure, configuration of the racket, sample size and time to test.

3.2.5 Testing

An overview of the test protocol is shown in table 3.2

Usually in each interview test, subject to the availability of participants and time constraints, two experienced tennis players were asked to fill out a selection of data sheets (Appendix 1 and 2). The data sheets were a way of compiling background information about test participants and their racket choices. To begin the test the two players were asked to undergo a brief warm up including a limited number of tennis shots with their own racket. Separate interviewers individually conducted recorded interviews with each player simultaneously. Wireless radio transmitters were used to allow microphones to be attached to the players throughout the test without inhibiting play. A microphone and transmitter were also attached to each interviewer. The inputs from the microphone radio receivers were combined through a digital mixer and the interviews were recorded in stereo onto a minidisk player, with each microphone recorded to a separate stereo track. This enabled each individual's speech to be heard in a different earpiece when listening back to the recording playing from the minidisk player through earphones. Any incidence of interviewer and interviewee talking over each other and any confusion as to who was speaking at any particular time could then be clarified according to which ear piece it was heard through.

Table 3.2 Test Protocol

Participants filled out information sheets and consent forms	5 minutes
Warm up	5 minutes
Players hit to each other with a test racket each until they were ready to comment on it	70-80 minutes
Interviews conducted separately at the same time with each player	
Test continued with the remaining rackets until the end of the available court and player time	
Players asked for feedback on the interview process and thanked for their participation	5 minutes
Total time	1 hour 30 minutes

The players were presented with rackets according to a predetermined Latin square ordering. Contrary to its usual application, this was to ensure that a variety of ordering effects were experienced by different players in an attempt to elicit a wider variety of commentary and vocabulary.

Players were tested after real play situations so they would use a variety of shots in an open skill environment thereby stimulating as wide a vocabulary as possible. To streamline the protocol, two participants played non-competitive constructive rallies with each other, working through a variety of shots and according to their own preference, and were tested at the same time. The nature of this arrangement meant that the players had to rally with each other using different rackets. This did have an affect on the ordering of the racket presentation in some cases. Since the objective was to stimulate the use of vocabulary, rather than to directly compare rackets, ordering effects introduced by this compromise were not considered to be a detrimental factor.

Players were asked to play with each racket until they were happy that they had a good feel for it, usually this meant about five minutes of play. The subsequent interview continued until the player had exhausted their comments on the current racket. Each test lasted around one and a half hours and usually allowed for the eight rackets to be used, in some cases more or less rackets were tested according to the available time.

Following procedures described by Patton (1990), the interview was guided, but largely conversational in nature and relied on the extreme characteristics of the rackets to stimulate players to use a more extensive vocabulary. Verbal prompts or questions that might have suggested vocabulary to the players were avoided. Aside from the opening statement, questioning throughout the interview was open, i.e. it required a dialogue response rather than a binary monosyllabic answer and only addressed issues and used vocabulary that had already been brought up in the test. This reflective reiteration of vocabulary and issues is referred to as ‘probing’. Players were probed about issues that needed definition or more clarity or for example, to attempt to discover further relationships.

Each interview was opened with an explanation of the study and general information relating to the interview. The following passage was then recounted to each player:

> “I would like you to have a number of rallies with each racket, when you are ready I want you to explain/describe what factors have influenced your overall impression of each racket”

A list of racket characteristics seen only by the interviewer provided a point of reference to give a loose structure to the interview should a player not be forthcoming with commentary, or fail to cover an area of particular interest (Appendix 3). The racket characteristics model, described in the rackets section above, was used to focus the list of characteristics to fifteen anticipated main areas as follows:

- Flexibility
- Strings
- Cosmetics
- Length
- Grip
- Sound
- Weight
- Moment of Inertia
- Racket Material
- Head Size
- Vibration
- Brand
- Age
- Wear
- Performance

Further questioning followed to establish the nature of the descriptors appropriate to each characteristic, e.g. did the descriptor imply that the particular characteristic was good or bad.

Exceptions to the Latin square ordering were made if it was felt that a particular response, that had previously gone unnoticed by the player, might be stimulated by a particular racket, which could be used prematurely to help progress the interview.

If there was time remaining after the main interview was conducted, a method described by Patton (1980) utilising imagery was incorporated to try and stimulate use of additional vocabulary. Each player was instructed as follows:

> "Now picture yourself playing an ideal game with the ideal racket. Talk me through the experience including any contributing factors that the racket provides. Where in the game are their perceptions most intense?"

The resulting description was probed for clarification or to expand on particular points of interest.

At the end of each testing session all the interviews recorded on to minidisk were copied on to compact disk to both secure the data in a more permanent medium and provide a convenient format for transcription.

3.2.6 Evaluation of Testing

Freshly opened Penn titanium tennis balls were used for the majority of tests. The only exception being in Cologne, when two of the earlier tests were conducted with freshly opened Wilson tennis balls due to a delay in availability. Although some of the tests experienced problems with missing participants, they generally ran to time and generated a wealth of data.

All twenty of the test rackets were available for the tests in Cologne, although for the majority of the tests only the eight core rackets were necessary. The rackets were ordered according to a Latin square arrangement to ensure a variety of ordering effects to encourage a greater range of stimulus. Towards the end of the second day of three, the strings of the Keubler R50 and Head IX16 rackets broke, so other rackets had to be substituted in for subsequent tests. The substituted rackets were chosen by trying to match the extreme characteristics of the rackets they were to replace (e.g. the Kuebler R50 was replaced by the Prince Longbody Ripstick since both had extreme characteristics of vibrations and flexibility, although they are at opposite ends of the scale).

The first substitution was the Dunlop longbow for the Kuebler R50, for the next test this was replaced with the Prince Longbody Ripstick, and when the IX16 strings broke the IX16 with a disabled chip was substituted.
For the German tests in Cologne all interviews were, as far as possible, conducted in both English and German. This meant that the English results could then be validated against the German translation and meant that people at Head could use the German versions for their own research. The process meant that the interview could be conducted in English, allowing English speaking interviewers to follow the interview

and apply appropriate probes, but also ensured the German speaking players could reiterate their points in their own native language at the end of each interview allowing them to utilise the full wealth of their tennis specific vocabulary without the restrictions of translation. A weakness of this arrangement was that when the participants spoke in German, responses often became a monologue summary of the English interview, making it difficult to track whether all the appropriate commentary and results of any probing were included and limiting the opportunity for further questioning. Further to this, the additional time taken to conduct each interview in two languages meant that playing time often had to be reduced or the interviews conducted in less depth.

At the testing in Head UK's Cheltenham test centre, six players were expected to participate in the tests, of those, five were actually available. This meant that one of the players had to play twice so that the fifth player could rally with each of the test rackets. The player participating twice was not interviewed a second time, and merely acted to feed balls to the fifth player.

On the day of testing at Bedford 4 participants arrived all at the same time due to a communication error made by the coach. Since all the players only had 1½ hours available the decision was made to test all participants simultaneously. Two players were asked to hit balls to each other whilst the other two were interviewed on the rackets they had just played with, then the players would swap so those being interviewed would start to hit with the next rackets and the players who were hitting would be interviewed. In this way two interviews were recorded on each minidisk, and later separated during transcription. Whilst on the surface this method might appear to be a very efficient way of conducting the interview tests, in practice it only lengthened the whole process and had some undesirable consequences for the participants and interviewers. The interview time often out ran the play time, which inevitably meant that players were left idle waiting for the previous interview to finish. This also meant that the intensity of work for the interviewers was high, leaving no time for preparation between interviews. Data analysis was also more difficult since interviews were recorded on the same tape and extra care had to be taken when transcribing and coding the data so as not to confuse it.

3.2.7 Transcript analysis

The minidisk recordings from the interviews tended to be around 80-90 minutes long. Some interview recordings of poor quality and had to be discarded; 3 German tests were discarded from 18 participants, and 2 English from 17 participants were eliminated for this notion. Those that were good enough to be used were transcribed by a selection of 5 reliable people with some relevant experience. Each transcriber was asked to follow guidelines outlining the level of detail and content that was required and how to present the transcripts. The small selection of transcribers and guidelines helped to maintain consistency between transcripts.

There were concerns about how German phrases might be construed in English, with potential for vocabulary to be lost in translation. In an attempt to maintain the completeness of the data, the German was, as far as possible, translated into English directly rather than rephrasing to sound more eloquent, so as to minimize the distortion of the language or vocabulary

In total 30 participant interviews were transcribed from over 40 hours of minidisk recordings, with each English interview averaging 4000 words per transcript and each German interview averaging around 9500 words per transcript. The German interviews were inherently longer due to the fact that each interview was conducted in both English and German.

All the interview transcripts underwent a process known as ‘clustering’. “Clustering involves comparing and contrasting each quote with all the other quotes and emergent themes to unite quotes with similar meaning and separate quotes with different meanings” (Scanlan et al. 1988) In this case the quotes from the transcribed text were classified, or coded, under a descriptive title called a node. The software package used to classify all the text was N6 QSR NUD*IST. NUD*IST could import full transcripts in the form of a text file, which could then be worked through, selecting quotes and vocabulary from the text. The selected text is coded under user-defined nodes. Each node can be accessed individually at a later date and all associated coded quotes displayed. NUD*IST has many statistical analysis functions. One of particular use was the ability to search for sections of text coded under one or more nodes, thus indicating a relationship between the nodes identified.

The English interview transcripts were clustered into 253 nodes each containing a number of quotes and examples of related vocabulary. Clustering of the German testing resulted in 279 nodes. The slightly higher number of nodes could be explained by the inclusion of some German phrases and the differences in use of language from English.

The clustering process usually took between 4 and 6 hours for each transcript. Given 30 transcripts from both UK and German studies a total of around 150 man hours were dedicated solely to this task.

3.3 Structured hierarchy formation

Normal practice (Roberts 2002, Davies 2003) has been to associate a unique descriptive but terse name with each node. Whilst feel maps constructed using only the node name are adequate for interpretation by those that compile them, they are less useful to those that are less expert. To improve the method a representative simplified for of the statements associated with each node has been introduced to the feel map in this case.

The map node entities were constructed using Microsoft Visio software from the assigned name and simplified quotation. Although this might be thought to add ‘clutter’ to the map, it was helpful as further explanation of the nodes. This subsequently aided in the construction and the application of the model by allowing quicker and easier reference.

Similarly related nodes were grouped together in large clusters on the Visio drawing screen. Within each cluster highly related nodes were linked to base or sub themes. Related base and sub themes were in turn linked to general dimensions forming a basic structure as shown in figure 3.3:

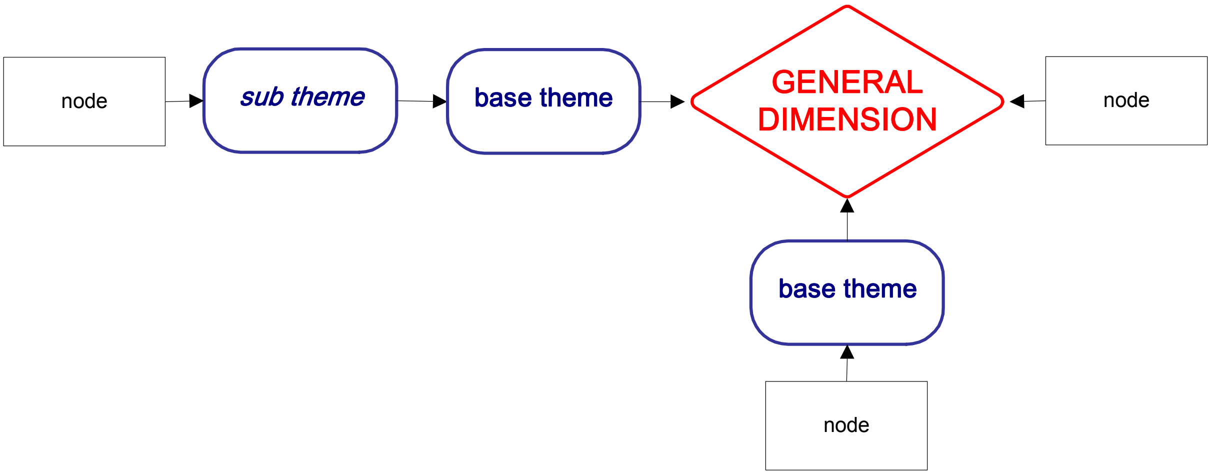


Figure 3.3 The basic hierarchal structure of the perception relationship model

The structure was reviewed to ensure that base themes represented a definable characteristic of the general dimension and that sub themes represented a characteristic of the base theme.

The model was also checked for redundancy, particularly with reference to base and sub-themes but also in some cases with nodes and general dimensions. Redundancy of sub-themes is most commonly the result of repetition through opposition, through reassignment of nodes or through unbalanced hierarchy of themes.

Repetition through opposition was generally very obvious, with base or sub themes describing the same characteristic but at opposite extremes. In the example shown in figure 3.4, heavy and light are opposites, both describing the same characteristic, i.e. weight, and are therefore redundant

.

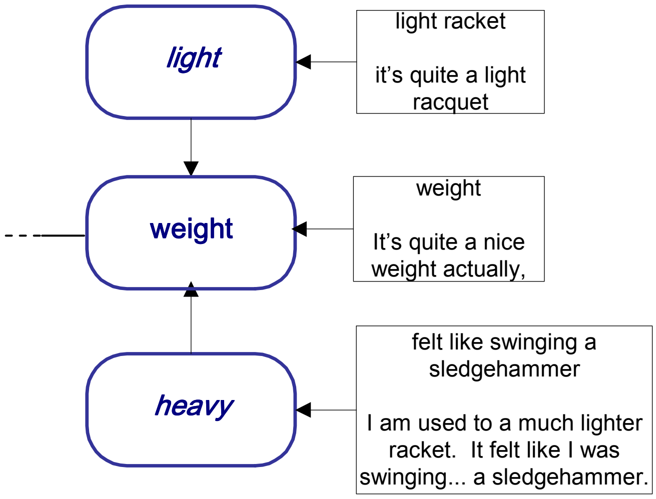


Figure 3.4 Repetition through opposition

From this same example a redundancy also exists through an unbalanced hierarchy. This was usually indicated by a node with the same or similar label or description to that of the base or sub theme above it. In some cases the node would have a similar label to the base or sub theme it was connected to, but neither would be redundant. In these cases the participants have merely referenced a higher order theme in their response. A clear indication of this would be the existence of other nodes connected to the same sub theme, but to truly validate the sub theme, it would be tested as above to verify whether it was a genuine characteristic of the higher order theme. The same could apply at any level of the model. The example shown in figure 3.5 shows the node ‘light racket’ is similar to the sub theme ‘light’ which it is connected to. The sub themes are also descriptors rather than definable characteristics of weight so as such are redundant. It should be noted that the node ‘weight’ is the same as the sub theme it links into. Since the base theme weight will have other nodes connected to it and is a genuine characteristic of the general dimension, ‘inertia properties’ it links into, neither is redundant.

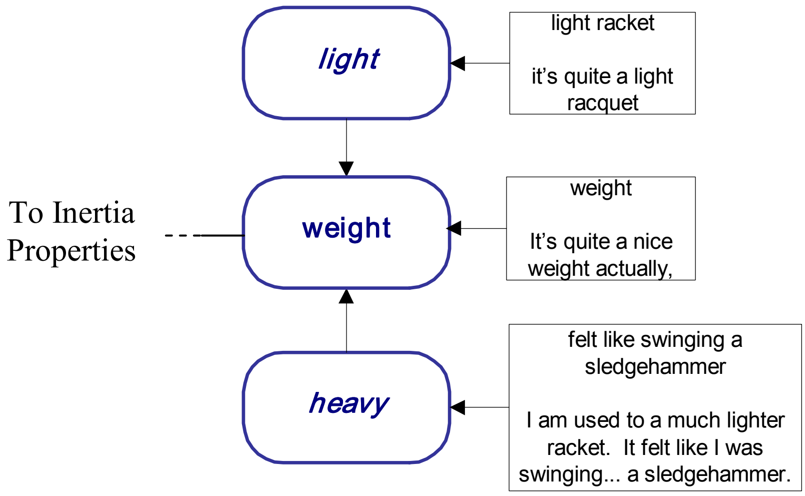


Figure 3.5 The unbalanced hierarchy

The model was also checked for completeness. Each grouping was examined to assess whether there were any gaps in the structure that might be able to be filled. In most cases gaps could be filled by unifying existing sections of the model. The example depicted in figure 3.6 shows that if the feedback cluster is checked for completeness it can be seen that although vibration might be an expected characteristic of feedback, this base theme is absent from the cluster.

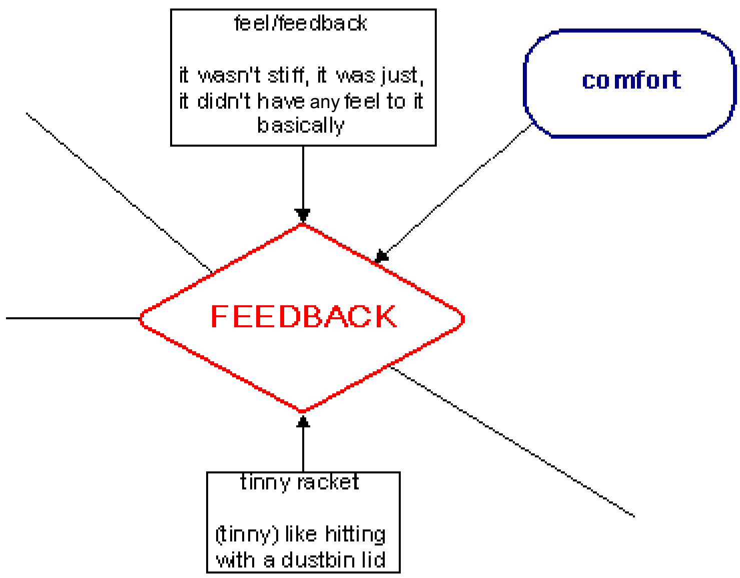


Figure 3.6 The general dimension of feedback is checked for completeness

Further investigation might have revealed that although vibration exists in the model it is classified as a general dimension of its own cluster. Scrutiny of the cluster reveals that it has no base themes, and has nodes which are related to feedback and comfort as can be seen in figure 3.7.

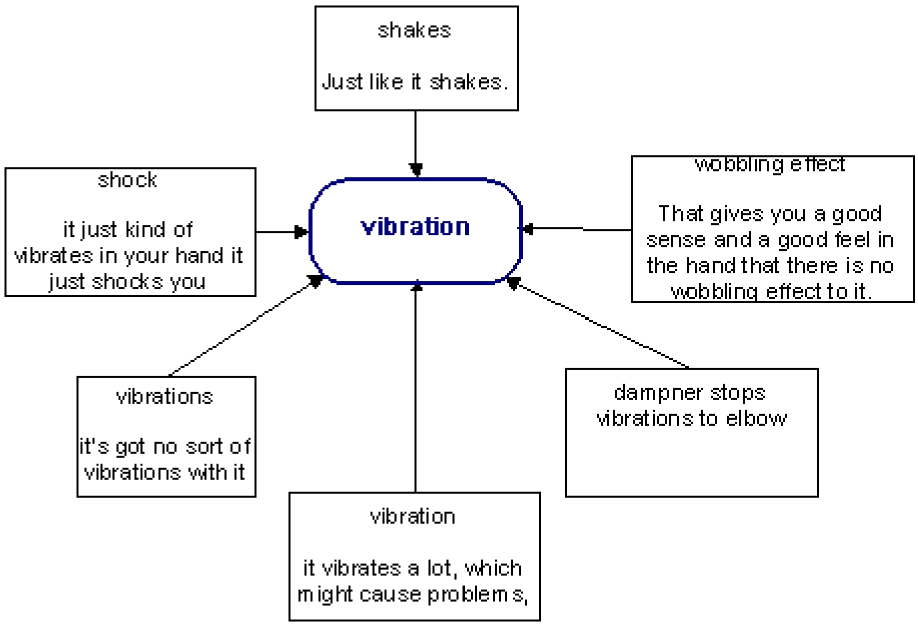


Figure 3.7 Vibration as a base theme of feedback

It is apparent that this cluster would make the feedback cluster more complete and so this amendment would be made.

The final check for completeness examines the nodes associated with sub or base themes. In most cases it is appropriate to have nodes that are an assessment of quality and those that are an assessment of quantity. If any base or sub theme appeared to be missing one or other category of node then this was searched for elsewhere in the map structure and within the clustered transcripts incase it might have been missed or incorrectly assigned.

3.4 Interdependency identification

The flexible N6 QSR NUD*IST search function, mentioned previously, was used to output all text that was coded under two or more nodes. Text coded under more than one node was likely to highlight a relationship between the nodes. This simplified the task of identifying any interdependencies existing between nodes, sub-themes or general dimensions. Interdependencies make up a vital part of the relationship model. To represent them in the Visio model, green dashed lines were used to link the related categories. Each of these lines was labeled to give an indication of the nature of the interdependency.

3.5 Summary

The perception relationship model, or feel map, was developed as a tool to be used in perception related testing. Quotes and vocabulary from guided player interviews formed the basis of the model. Transcripts from the model were analysed using NUD*IST software which allowed the user to classify text into groups called nodes. Nodes were copied into a design package, Microsoft Visio, which allowed related nodes to be grouped together. These groups were organised so that a basic structure was in place, linking nodes together around a general dimension, via base and sub themes. NUD*IST was again employed to route out relationships between nodal groups that were dependent upon each other. These interdependencies were marked on the model linking the structured groups. English and German models were compiled for comparison as a form of validation.

The feel map visualises the relationships that exist between player perceptions and informs the user of the associated tennis specific vocabulary used to describe these perceptions and relationships. This makes the map a useful tool to assist in the creation of more educated tennis perception questionnaires, as an informed guide for perception investigation and as a racket design aid.

The data presented in the feel map is broad, and the user has no assisting information to indicate which areas or examples of vocabulary are most appropriate for use in any particular application. The strength of the model could be improved by providing some additional guidance a more effective application.

One method of attaining and including data in the map that would address this issue utilises a postal questionnaire. Information relating to the relative importance associated with racket characteristics and the percentile use of any vocabulary in the model would be compiled from the questionnaire.

Chapter 4 details the development and implementation of such a questionnaire. The methods of analysing and including the data in the feel map are also reported. The resulting adapted feel map is also discussed in comparison with the unmodified German map

CHAPTER FOUR

MODEL VALIDATION, ENHANCEMENT AND COMPLETION

4.1 Introduction

The work undertaken to clarify and associate player interview statements within representative statement type entities into common entities resulted in a hierarchal perception relationship model linking associated statement types together via sub themes to nominated general dimensions of racket characteristics. To more fully address the research question, ‘Can subjective player perceptions be correlated to objective performance measurements to enable design optimization leading to superior rackets?’ some form of test questionnaire is required to investigate player perceptions in a consistent manner underpinned by the model.

The feel map can be used to identify a range of issues and vocabulary that relate to a particular racket feel phenomenon. This information can be usefully employed to create a questionnaire that utilizes tennis specific vocabulary and questions that target areas relating to the characteristic under examination. In many cases the tennis specific vocabulary available from the feel map is very extensive and in previously published forms the researcher has no external information to help guide the decision as to which is most appropriate to best avoid misinterpretation. Furthermore, as is the case in this research, when time is restricted and only a limited number of areas of player perception can be investigated the feel map does not offer any guidance as to which areas should be prioritized as most important to tennis players’ overall perception of a racket.

Thus to strengthen the English map and broaden its application, the following additional research is important:

- Validation of the collated vocabulary to ensure classification has been correctly assigned and to identify other possible interdependencies

- Establishing percentile use of the collated vocabulary to identify most commonly understood terms for higher priority use together with synonyms for validity checking

- Determination of the relative importance of the identified general dimensions of feel

- Determination of the ideal racket characteristics with respect to the identified general dimensions of feel

A series of questionnaires to address each of the above issues was constructed and distributed to a larger population of appropriately experienced tennis players via email invitation to complete the questionnaire via the internet.

This chapter presents the design of these additional questionnaires associated with the above issues together with an analysis of the participant responses and other enhancements to complete the model.

4.2 Questionnaire Distribution

Distribution of the questionnaire had to be effective at reaching a large sample whilst remaining within the budget and time restrictions of the research.

One option was to post out questionnaires to clubs and players around the country. This method would reach a large sample size but requires replies by post, which would make it somewhat inconvenient for participants reducing the return rate and increasing the time required to collect the data. Furthermore the processing of the collected data would also be very time consuming, with considerable effort required just to enter it into tabular form.

Alternatively, personal delivery of the questionnaires to clubs and teams would ensure a high return rate, but would still require lengthy processing and would be costly in both time and cost in travelling to clubs and county associations around the country.

As a means of tackling the negative aspects of the other methods a questionnaire was posted on a website that could automatically compile the results into a database. The web page URL's were then emailed to county associations, clubs and players around the country quickly and easily. County associations and clubs were asked to pass on the link to their members. In this way it was possible to contact a sample of between 500 and 1000 participants.

To encourage players to complete the questionnaire a prize draw was contrived whereby players who participated would be entered and the winner given a racket of their choice from the Head range.

Macromedia Dreamweaver 10 software was used to build the web based questionnaire. The software made it quicker and easier to create a clear and aesthetically pleasing layout for the questions that could be repeated throughout the questionnaire. Extensive programming was required to link sequential pages of the questionnaire together whilst instructing the software how to register participant responses and to compile the appropriate information into a database. The database itself needed to be setup to receive and archive the data from the questionnaire in a clear and well structured manner so that it might be exported at a later date for analysis.

4.2.1 Participants and Distribution Details

The first drafts of the questionnaire were emailed to 5 participants as a pilot test. A bug in the table assimilation programming and a number of incorrect links were discovered and corrected before full distribution. Subsequently over 400 emails were sent to county associations, clubs and individual players, with instructions to disseminate the links to any available player contacts. All the players were asked to assess their own approximate level of ability. 137 responses were logged from the website, the majority of which assessed themselves as ‘club’ level (70%). 82% of the respondents rated themselves at this level or better. A more detailed summary of the sample can be seen in table 4.1:

Table 4.1 Summary of the questionnaire response sample

Playing Standard	Number of Participants	Percentage of Total Sample (%)
Recreational	25	18.2
Club	96	70.1
County	11	8.0
National	4	2.9
International	1	0.7
All Standards	137	100

After the emails were sent the response rate was monitored from the website after 6 weeks the rate of return had slowed significantly and data collection was finally discontinued at 8 weeks.

4.3 Questionnaire design

4.3.1 Vocabulary Percentile Use and Model Validation

Distinguishing the percentile use of vocabulary provides the user with vital information that helps them select terminology that would be best understood by the broadest demographic, and less likely to be misinterpreted. This process also helps to cross check and validate the perception relationship model structure. This is important to ensure that vocabulary has not been classified incorrectly. It also helps to identify additional interdependency links within the model.

To determine percentile use of vocabulary the frequency of occurrence in the guided interview transcripts could be analysed to assess the percentile use of specific vocabulary used to address a particular perception issue. The frequency could be construed as an indication of the population’s percentile use of vocabulary, arguing that more common vocabulary will be brought up by more participants. The results from pursuing this argument are likely to be misleading because:

- Participants might speak at length about a subject they are less familiar with since their attempts to convey meaning are less concise.
- New or unusual issues are likely to be probed more extensively by the interviewer, thus artificially increasing the frequency of occurrence.
- Players might in fact more commonly address issues that are easy to diagnose rather than necessarily being more prolific within the tennis community.

To provide data for the percentile use of the tennis specific vocabulary identified from the previous interviews one section of the proposed questionnaire needed to be designed to elicit this information.

One possible structure for these questions was to list all the vocabulary from the model and ask the user to state or select a category or general dimension that it relates to. This method would ensure that all the vocabulary is considered and classified or disregarded as appropriate. The disadvantage of this method is that with almost 300 nodes and associated examples of vocabulary and quotations and 12 general dimensions it would be over complicated and confusing to the user. Thus it would take considerable time to complete, particularly if it takes the user some time to become familiar with and adapt to the presentation format to respond appropriately to the questions.

An alternative method was deemed to be more appropriate since it appeared to be more "user friendly". The user was presented with a question followed by a list of selected vocabulary. The question would ask "Please indicate which of the following words or phrases is appropriate to describe the racket *characteristic*", and the user would select either, "used" or "not used" for each of the example quotes listed. To validate the feel map, the list of example quotes included vocabulary that appeared to be appropriate, which might be related from within the same map cluster, and some from various other clusters that, based on the feel map, appeared to be unrelated. Thus it would be possible to not only establish a percentile usage of the vocabulary, but also identify vocabulary that might be incorrectly assigned within a group structure and potentially uncover new interdependencies. The unrelated quotes acted as a cross reference that the answers given were accurate and that the user had understood the question. Figure 4.1 presents a sample page from the resulting questionnaire.

Q. Please indicate which of the following words or phrases is appropriate to describe the racket **control** ?

Not Used		Used		Not Used		Used	
			It was quite a control racket				The racket is real good for touch
			The racket does what it wants				It has power without control
			Feel a nice connection				This is a racket for beginners
			Kept catching the frame trying to put spin on the ball				Its harder to find the centre of the racket
			The racket's quite big for running out wide				The racket is hard to maneuver
			It mentally looks like the racket is going deeper				The racket restricted my swing
			Can hit anywhere on the racket but obvioiusly the middle is best				The racket means your timing is out
			Shots die off centre				Seems like I was hitting a mishit every time
			It has thick strings				The racket is handle heavy

Figure 4.1 An example percentile use of vocabulary question

4.3.2 Interpretation of the vocabulary

To identify whether vocabulary was intended to convey a positive or negative assessment of the associated racket characteristics the question structure was further revised. The user was asked to not only select which quotes were “used” or “not used”, but also whether they were negative or positive assessments of the characteristic. The user was presented with the options “not used”, “negative”, “neutral” or “positive”. Figure 4.2 shows a sample question from this piloted questionnaire format.

The questionnaires pilot testing revealed that the user often struggled to understand the concept of rating vocabulary as negative or positive, which led them to skip questions or rate everything as neutral. As a result the positive and negative options were removed from the format so as to help reduce user confusion and improve the quality and quantity of responses.

Q1. Please indicate which of the following words or phrases is appropriate to describe **how familiar or unfamiliar** a tennis racket **looks**?

Not Used		+ive	Neutral	-ive		Not Used		+ive	Neutral	-ive	
☐		☐	☐	☐	Weird head shape	☐		☐	☐	☐	Old fashioned
☐		☐	☐	☐	Cumbersome shape	☐		☐	☐	☐	Egg shaped
☐		☐	☐	☐	Chunky frame	☐		☐	☐	☐	Strange shape
☐		☐	☐	☐	Goes like a rocket	☐		☐	☐	☐	Mishit a lot
☐		☐	☐	☐	Shape makes it feel longer						

Figure 4.2 An example of the piloted interpretation of vocabulary question format

4.3.3 Relative Importance

Determining the relative importance of tennis racket characteristics provides the user with valuable information to prioritise areas for research, as well as aiding the selection of questions in the development of test questionnaires and feedback forms. Thus a further questionnaire section to address ‘relative importance’ was necessary.

In an attempt to establish relative importance, as with percentile use of vocabulary, the guided interview and resulting transcript clusters could again be analysed to assess the frequency of occurrence of issues or perceptions within each interview and across the whole sample. This frequency could also be construed as a suggestion of importance of the characteristic to individual players or the whole sample, based on the argument that more important issues will be brought up more often and by more participants. Again the same weaknesses listed in the previous section undermine this argument (Section 4.2.1).

One presentation format considered for this section of the questionnaire was to list characteristics taken from all the group clusters of the model and ask the player to rank the characteristics in order of importance. This was thought to be a quick and easy way of assessing the relative importance of the characteristics in a way that was simple to understand for the user. One disadvantage of this method is that no two characteristics can be rated with the same importance and there is no way of knowing whether, for example, three characteristics are far more important than any of the other characteristics in the list. Perhaps more importantly, the method is also vulnerable to human error since the participant is expected to hold the whole list in mind whilst positioning each characteristic.

A pair-wise comparison of the list was also considered. All the characteristics on the list would be compared with each other in separate questions asking the user to choose whether one is more, less or the same importance as the other. This method would help reduce participant error and would be effective in establishing a rank importance but would require a lot of questions. Every issue would have to be compared with every other in the course of the questionnaire; for example, with all 12 general dimensions questioned, a pair wise comparison would result in 66 questions. With the questionnaire already fairly long, and concerns about the return rate, increasing the length of this section of the questionnaire by these proportions was not desirable. This method also failed to address the issue of establishing whether an issue might be very slightly more or very much more important than the one eventually ranked below it.

The third approach considered would allow the user to rate the level of importance of a characteristic on an ideally analogue scale. The characteristics would be listed alongside a sliding scale, which would allow the user to rate the importance of each, relative to the rest of the list. Since implementing a truly analogue scale using Dreamweaver is not possible a scrolling integer list increasing from 1 to 100 was used. The small increment relative to the size of the scale permits it to be used as an analogue scale to the same accuracy as a mark on a 10 cm line measured to the nearest 1 mm. This approach was chosen for the questionnaire since the user would have the freedom to rate some characteristics much higher than others and would not have to answer such a large number of questions. The questions in the section of the questionnaire addressing relative importance were all written to the same format to maintain consistency between answers. Figure 4.3 shows a sample page from the online questionnaire.

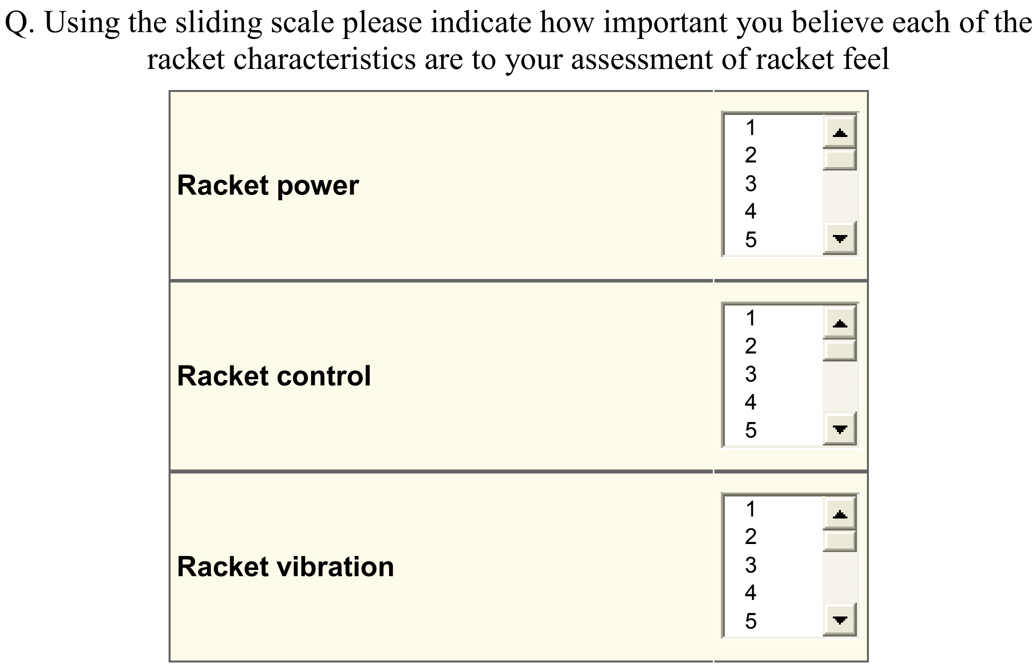


Figure 4.3 An example of the relative importance questions

4.3.4 Ideal Racket Qualities

Establishing what players would consider to be the “ideal” racket would provide the user with useful information to help guide future development and to assist in interpreting player feedback. Although producing designs to meet an ideal specification devised from the averaged responses from a group of individuals inevitably results in a product that dissatisfies most people least, polling users’ preferences does at least identify those characteristics most commonly thought desirable and perhaps may yield consensus.

To some degree a player's ideal racket qualities could be deduced from the previously conducted player interviews. In many cases participants expressed their own personal preferences when referring to a particular racket characteristic. Although this method would give a reasonable indication of ideal racket qualities, the technique does not necessarily yield a complete description since not every player made reference to the same racket characteristics, leaving substantial gaps in the data for most individuals. Furthermore, a sample size of 20 individuals would be too small to draw firm conclusions as to the most desirable characteristics, on average, amongst the wider population of all tennis players.

Another option was to arrange for a section of the questionnaire to ask players to describe ideal racket qualities. Each characteristic would be referenced in a series of questions and the participant asked to openly explain what would be ideal in a racket for them. This technique had the advantage of being able to reach a large sample through the questionnaire medium, and also ensured that participants commented on all the same racket characteristics by specifically questioning them. Despite its advantages, open questioning in this way creates difficulties in quantifying the returned data, particularly when the sample is large. Responses would have to be read individually and some subjective assessment made on its content to attempt to quantify the data. This process would be far too time consuming and vulnerable to interpretive inconsistencies.

Closed questions were identified as the best solution to reduce processing time and provide better consistency in the data. To help reduce any chance of the participant misinterpreting these closed questions vocabulary from the perception relationship model was used. As it is often asserted, Blair (2003) reports that the MIT, USA, Sports Innovation Centre's research experience suggests that the majority of human beings cannot consistently discriminate preference on a scale finer than five points. Thus, questions were constructed such that answers were made on a five-point scale of preference To aid understanding and reduce the chances of misinterpretation the positive and negative ends of the 5 point scale were labelled with appropriate quotes and/or examples of vocabulary that had emerged from the construction of the feel map. Figure 4.4 shows a sample ‘ideal’ racket question.

Q. How flexible would the racket be?

very flexible	flexible	neutral	stiff	very stiff
The there’s a lot of movement in the racket, fairly flexible			*The racket is hard, racket is like a plank of wood, it’s a stiff racket, the racket didn’t move much*	

Figure 4.4 An example of the ideal racket questions

4.4 Results Analysis

4.4.1 Common Techniques

The web based questionnaire was programmed such that each set of results was automatically compiled into a database. The database could then be exported to Microsoft Excel for analysis. For all sections of the questionnaire the data was sorted into player ability groups. The mean and median averages were also taken for all the data along with standard deviation values to give an indication of the spread of the data. This data is presented in the weighted lexicon crib sheet (Appendix 6) and is detailed further in Section 4.6.

4.4.2 Percentile Use of Vocabulary and Validation of Model

The percentile use data from the web based questionnaire was compiled as a series of ‘1’s’ and ‘0’s’, with 1’s representative of a positive result, i.e. the player was in agreement that they could recognise and might use the vocabulary in the given context, and 0’s equivalent to a negative result, i.e. the player could neither recognise or use the vocabulary in the given context.

A percentage of positive responses could be calculated from the data presented in this form, which with a large enough sample could be equated to the percentile use of the vocabulary in relevant population. This data was then transcribed into a weighted lexicon, with percentile vocabulary classified under sub themes and general dimensions according to the question that responses related to. Where a high percentile use was evident in more than one classification or, in a classification not considered before, the information was transferred into the perception relationship model i.e. a link of interdependency was introduced or the entity box re-classified into the appropriate group.

4.4.3 Relative Importance

The relative importance data from the questionnaire was compiled in the form of a percentage, with players selecting a higher percentage for more important issues and a lower percentage for less important issues.

To analyse this data the most appropriate statistical technique needed to be selected, more specifically what form of averaging should be used. The mode was discounted since this would highlight the most commonly occurring element, and in this case the scale was so fine that re-occurring elements were randomly distributed and would not represent the more popular choice. The mean average, calculated by summing the values and dividing by the total sample size, produces a number that generally is representative of the bulk of the sample, but can on occasion be distorted by random extreme results. The median is not adversely affected by extreme results but can be misrepresentative if large increments exist between adjacent values in the data.

Both the mean and the median averages were calculated and compared so that any major discrepancies in the two figures could be examined on an individual basis. The median value was used in the weighted lexicon and associated with all entities at or below the classification level of the question.

4.4.4 Ideal Racket Qualities

The closed nature of the ideal racket quality questions meant that the data needed little interpretation with points on the scale corresponding retrospectively to numbers one to five. As with the relative importance section both the mean and the median averages were calculated and compared so that any major discrepancies in the two figures could be examined on an individual basis. The median value was used in the weighted lexicon so that it would be in keeping with the five point scale used in the questions that research has suggested best represents the average person's preference.

4.5 Perception Relationship Model Extensions

4.5.1 Weighted Lexicon

To preserve the detailed information from the questionnaire responses a 'weighted lexicon' was constructed as a definitive reference tool complementing the feel map. The full lexicon is included in Appendix 6, a condensed sample of the lexicon is shown in figure 4.5.

Ref	General Dimension	Sub Theme	Vocabulary/ Quotation	Relative Importance			Percentile Use		
				%	**SD**	**n**	**%**	**SD**	**n**
1	Grip	Adhesion of Grip	its quite a slippy grip	75.85	22.44	51	45.1	0.5	50
1		Grip Adhesion	this grip would give me blisters				31.37	0.46	50
1		Grip Adhesion/ Material	it's a leather grip				29.41	0.46	50
2	Power	Achievable Pace	the ball flies/flew off racket	72.79	21.61	51	62.75	0.49	50
2			its very pingy/pings off quickly				35.29	0.48	50
2			the ball is popping off				11.76	0.33	50
2			power/pace				68.63	0.47	50
3	Control	Ball Control	difficult to time the ball	66.71	22.11	51	74.51	0.44	50
3			good for getting the ball in				33.33	0.48	50
3			struggle to know where the shots going				37.25	0.49	50

Figure 4.5 Weighted lexicon sample

The weighted lexicon was developed to complete the feel map. Users would be able to make quick and easy reference using the more visual feel map and then refer to the weighted lexicon where more precise or detailed information was required. The Lexicon is important to portray information in a format that can be readily assimilated and interpreted by marketing personnel, researchers and designers.

The weighted lexicon gives users access to the full range of vocabulary and, in many cases, its associated rating of relative importance and percentile use, which makes it much more useful in questionnaire construction. The associated data enables the practitioner to rank vocabulary and make educated decisions as to how best to construct questions. Having a wider range of vocabulary at their disposal should enable them to cross check responses by using alternative language in related questions. This form of cross checking could be used to tease out sensory confusion or explore completeness, where there appears to be gaps in the data.

The weighted lexicon not only gives the user the precise values for relative importance and percentile use, but also the total sample size and standard deviation of the data and the themes to which quotes have been coded. This data gives an indication of how trust worthy the data is, larger sample sizes and tighter distributions obviously providing more reliable data. The data with smaller samples and wider distribution can also be highlighted for further investigation to gather more supporting evidence of the figures.

4.5.2 Feel Map Graphical Rules

To further improve the feel map by making issues of percentile use and relative importance more apparent, the previous graphical representation techniques were improved on. Several formats were tested and after several revisions, and recurring problems with black and white publishing, the initial colour gradation format was abandoned in preference for a greyscale scheme. To maintain as much visual impact whilst making the technique more specific in detail the lines of the general dimension and sub theme boxes were thickened and coloured in greyscale to the appropriate relative importance level with darker lines representing higher importance in accordance with the following rules:

- General dimensions represented by a diamond with bold capitalised 12 point red text and 5 point line thickness.
- Base themes represented by a rounded rectangle with bold uncapitalised 10 point blue text and 2.5 point line thickness. Sub themes are represented in the same way with italic rather than bold text.
- Nodes represented by a rectangle containing name, simplified quotation and percentile use, 8 point, un-capitalised plain text and 1 point line thickness.
- Shade of general dimensions, base themes and sub themes box lines reflect the relative importance. The 100 point relative importance scale was represented by a percentage luminance with a luminance of 0 (black) equivalent to 100% and 240 equivalent to 0%.(white).
- Line thickness of nodes reflects the percentile use; percentile use corresponds to a percentage thickness with 3 point thickness representing 100%.
- Interdependencies are linked with dashed green 1 point thickness lines, labelled with 8 point, uncapitalised plain text.
- Black arrows link the hierarchy pointing from lower to higher order
- Anywhere on the map where no data exists, line thickness and shading is replaced with a dashed line of neutral shading and thickness i.e. representative of 50%.value.

Figure 4.6 shows the legend from the map summarising the rules stated above.

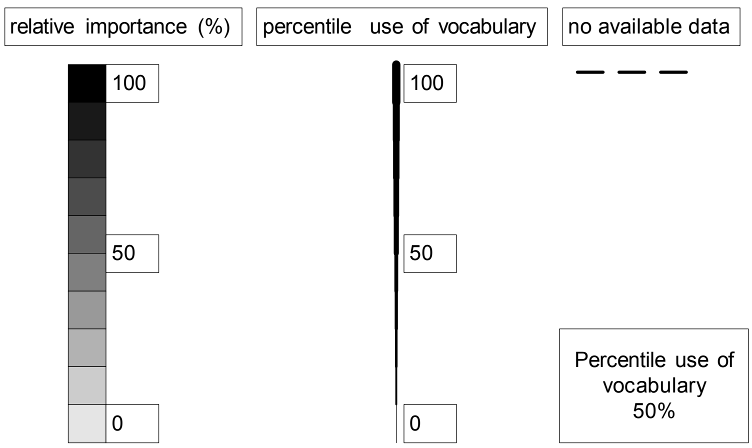


Figure 4.6 Feel map legend

Figure 4.7 compares the grey scale of two clusters from the map, one with a higher (a) and one with a lower (b) relative importance.

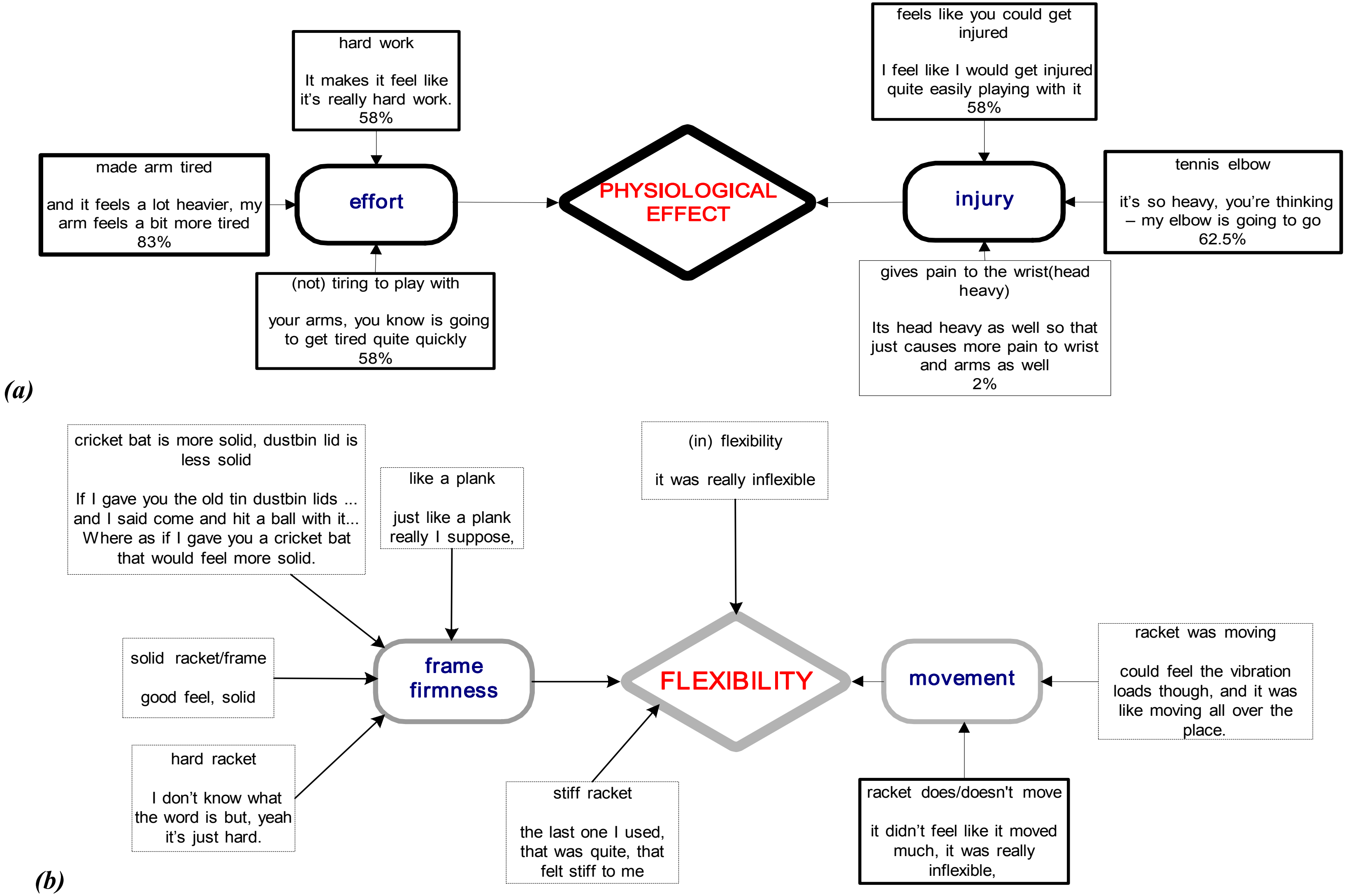


Figure 4.7 Comparison of high a low relative importance clusters

Note that although the box colour scheme was replaced by grey scale the text colour remained to add aesthetics to the map when colour printing was available.

Figure 4.8 demonstrates how the thickness of the entity boxes was used to represent the percentile use of the relevant vocabulary and an embedded number was added so further detail could be sort as necessary..

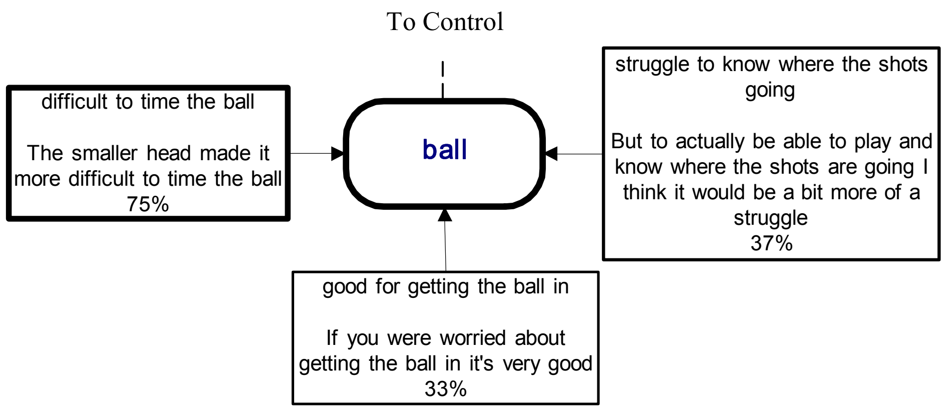


Figure 4.8 Example of node wall various thicknesses proportional to percentile use

Entity boxes were grey scaled according to the relative importance of the dimensions at higher levels in the hierarchy.

Figure 4.9 shows an example of how areas of the map with no data were represented by a dashed line of neutral grey shading and, in the case of entity boxes, equivalent neutral line thickness.

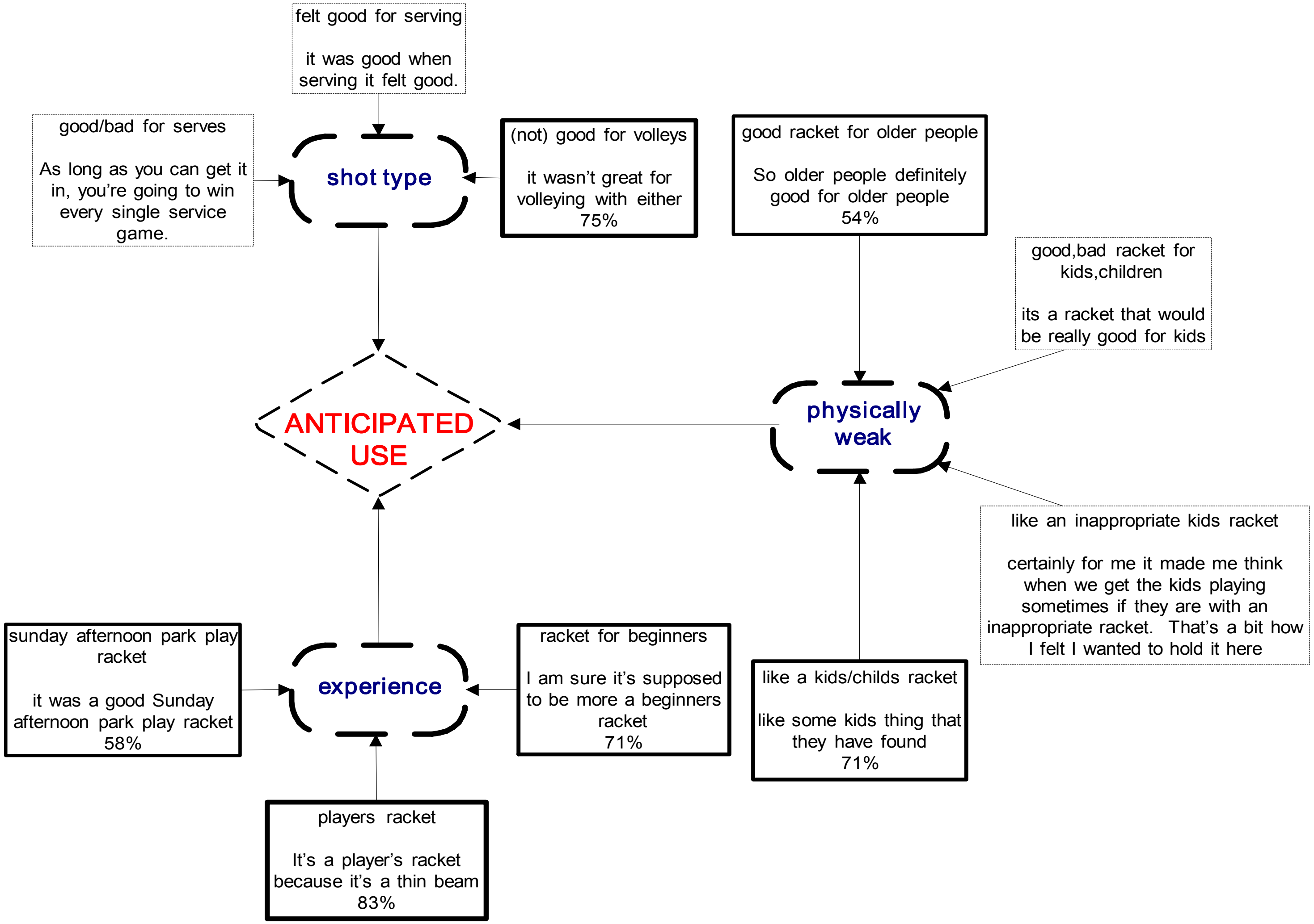


Figure 4.9 Example of dashed lines used where no questionnaire data was available

4.6 The final perception relationship model

4.6.1 Overview

The final model has 12 general dimension clusters as listed:

General Dimension	Relative Importance
Sound	79%
Grip	76%
Power	73%
Control	67%
Feedback	56%
Racket Dimensions	51%
Flexibility	30%
Anticipated Use	No data
Cosmetics	No data
Inertia Properties	No data
Physiological Effect	No data
String Bed	No data

It is perhaps surprising to see ‘Grip’ as the general dimension with the second highest relative importance above both Power and Control. However, this might seem to be more logical when the grip is considered as the only point of racket-player interaction, and thus the point on the racket at which the player experiences sensory feedback of many of the racket characteristics. With this in mind, it might also be expected that Feedback would also be rated highly, but this is not the case. This may be due to the players separating cause and effect, i.e. the grip is the point at which feedback is attained, and it is clear to the player that this is an important area of the racket, where as the feedback in itself is not such a tangible element of feel. Power and Control are both rated with high relative importance which is to be expected given that these are the two overriding factors affecting performance.

It is also worth noting that the standard deviations of grip, power and control are ~17, 22 and 22 respectively indicating that the order could be different if the testing were repeated, nonetheless all three are likely to be ranked similarly highly.

Further relative importance data was collected for the following base and sub themes:

General Dimension	Base Theme/Sub Theme	Relative Importance
Physiological Effect	Injury	84%
Inertia Properties	Weight	77%
Inertia Properties	Balance	62%
Physiological Effect	Fatigue	67%
Sound	Quality/Volume	40%
Sound	Quality/Pitch	31%

Injury has a higher relative importance than any of the general dimensions. It seems that players deem the injury risks associated with a racket to be the overriding most important factor affecting their perception of a racket. This is not at all surprising since it would be difficult to envisage a player using a racket that they believed to be injuring them or causing physical pain. It is also interesting to consider the high relative importance of the racket weight, which shares interdependency links with control and power. The high relative importance is perhaps reflective of its influence on these elements of racket performance. The low relative importance values associated by both volume and pitch are discussed in more detail in Section 4.6.2.

Careful presentation of such a number of sizeable clusters, to fit onto A0 paper, was important to maintain clarity in the model. The structure of each group was based on a star diagram to give some order to the large number of nodes, base and sub themes. Lines of interdependency were arranged to flow between clusters with minimal cross over and with well separated labelling to help reduce confusion when following lines through out the map (Appendix 8).

4.6.2 Sound

'Sound' is a well established large cluster in both the English and German feel maps (figures 4.10 and 4.11). There are 12 interdependency links in the English map compared with only 2 in the German, suggesting that sound is a more influential element of feel for the English players. This might again be attributed to cultural differences, but might also be due to the number of English interviews conducted indoors where, as is suggested by one of the nodes, sound might have a bigger effect.

As with many of the other clusters, a comparison between the English and German versions displays a similar structure, with many matching base and sub themes. The most pronounced difference is the perceived performance base theme that is absent in the German map. It is possible that the English players may have been introduced to the idea through coaching that sound can influence perception of performance, where as German players are not exposed to such subtle doctrine.

All except 2 of the 19 nodes with percentile use data have a rating of over 50%. Such a diverse and widely recognised vocabulary indicates how accustomed players are to discussing sound as an issue. It is interesting to note that whilst the nodes associated with the sub themes of pitch, volume and duration all have percentile use values well above 50%, the relative importance of pitch (31%) and volume (39%) is low. This is particularly surprising when the high relative importance of the general dimension of sound (79%). It is possible that when each quality is considered in isolation they hold less importance, than when they are considered as a whole, i.e. each element could enhance or compensate for another and none holds any overriding influence over the amounted qualities that make up the general perception of sound.

4.6.3 Grip

A similar structure can again be observed in the 'grip' cluster from both the English and German maps (figure 4.12 and 4.13). There are some differences in the variety and abundance of vocabulary for each base theme, as might be expected, but it seems that both sets of players perceive similar elements of the rackets characteristics.

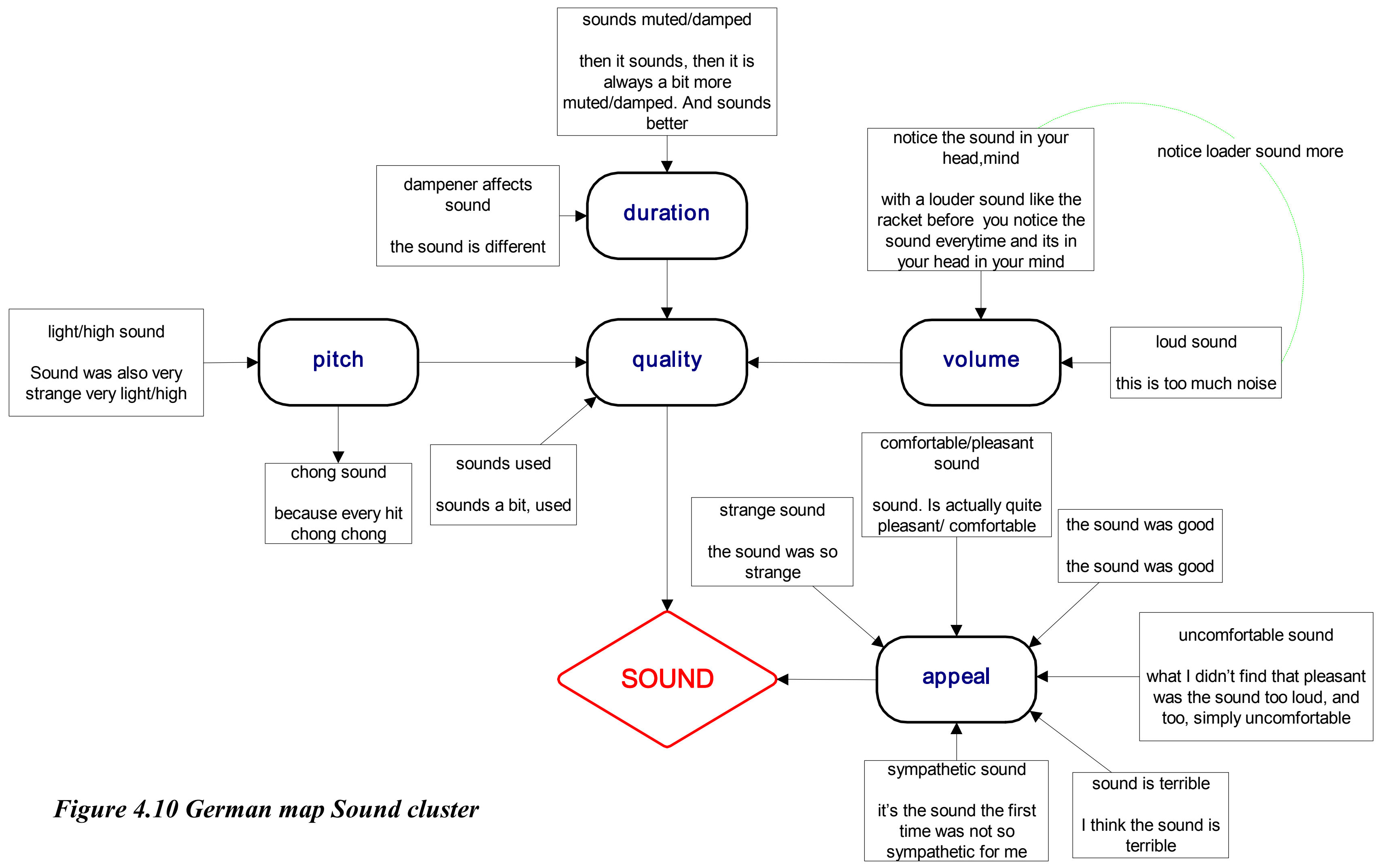


Figure 4.10 German map Sound cluster

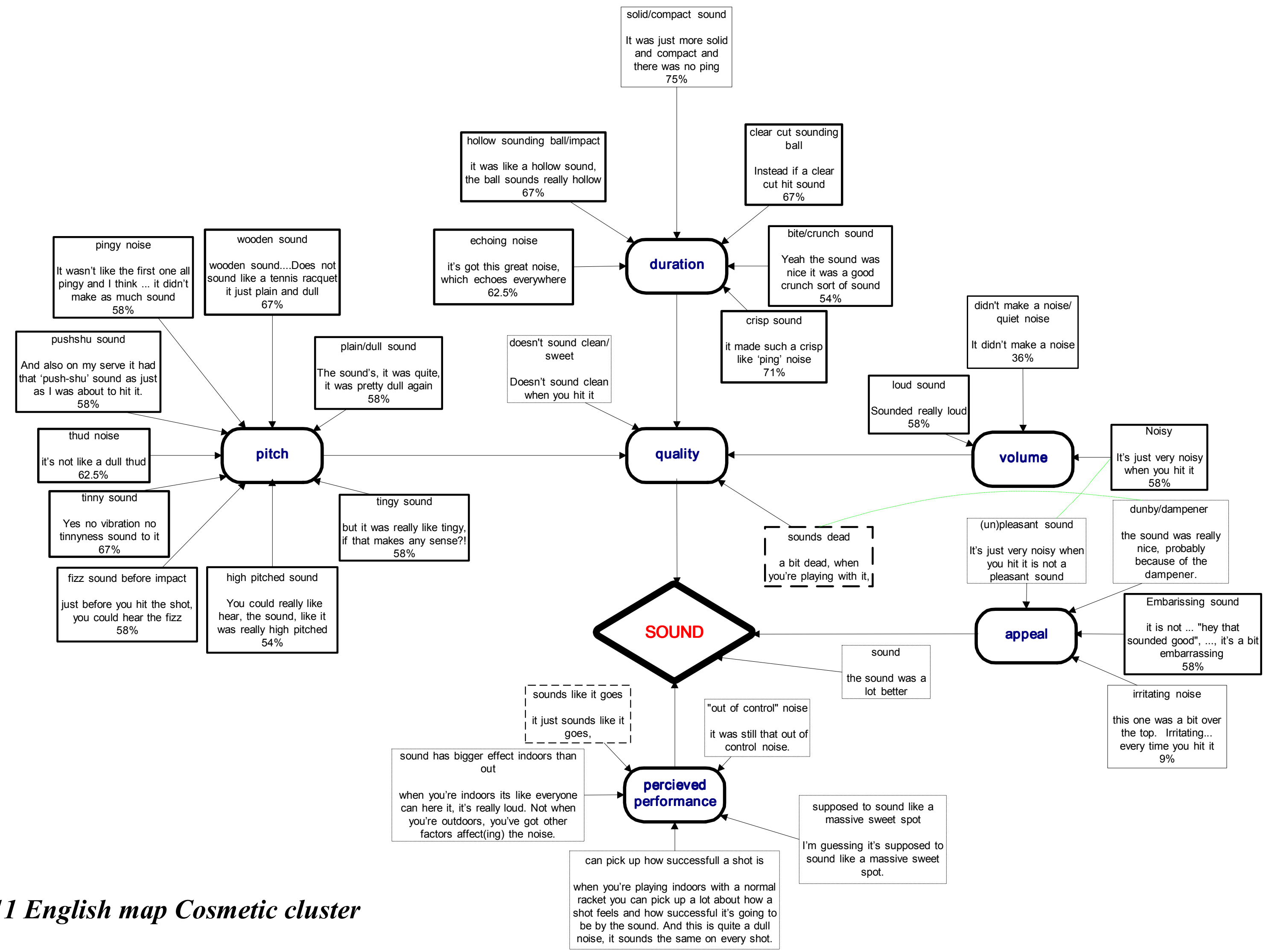


Figure 4.11 English map Cosmetic cluster

The highest percentage use of vocabulary values can be seen in the nodes directly linked to grip condition (‘grips wear well’ 73%) and those linked to it via grip age (‘old grip’ 70%, ’prefer modern grips’ 80%). This might imply that this is one of the more important elements of grip although there is no data to support this. It is at least apparent that players are accustomed to talking about grip condition. The impact of this area of the cluster was a little unexpected, but it is understandable when considered in context, since a player would probably find a grip in poor condition to be uncomfortable with poor adhesion, elements which would override the influence of the other aspects of the grip such as size or shape.

In both maps the grip cluster shares an interdependency with feedback and comfort. This confirms what might be thought an obvious relationship since the grip is the point of player and racket interaction. The English cluster also has 7 interdependencies, compared to 2 in the German map, suggesting that the English players believe grip to be more influential on other elements of racket feel. However, this might also be attributed to a limitation of the interview process given the language difficulties present in the German testing.

4.6.4 Power

The ‘power’ cluster from the English and German feel maps (figure 4.14 and 4.15) has a similar structure in each case. There are some differences in the variety and abundance of vocabulary for each base theme, as might be expected, but it seems that both sets of players perceive similar elements of the rackets characteristics.

In both maps power is not such a large cluster. This is surprising since with out exception all test participants referenced racket power in their interviews and the relative importance rating from the English model is one of the highest of all the clusters (72.6%). It seems that players are very familiar with power and commonly used, high-level specific vocabulary has developed as a result. This has perhaps stemmed from the emphasis of power placed on marketing by manufacturers. Also it is a fundamental goal in play and so a key discriminator in racket use and selection.

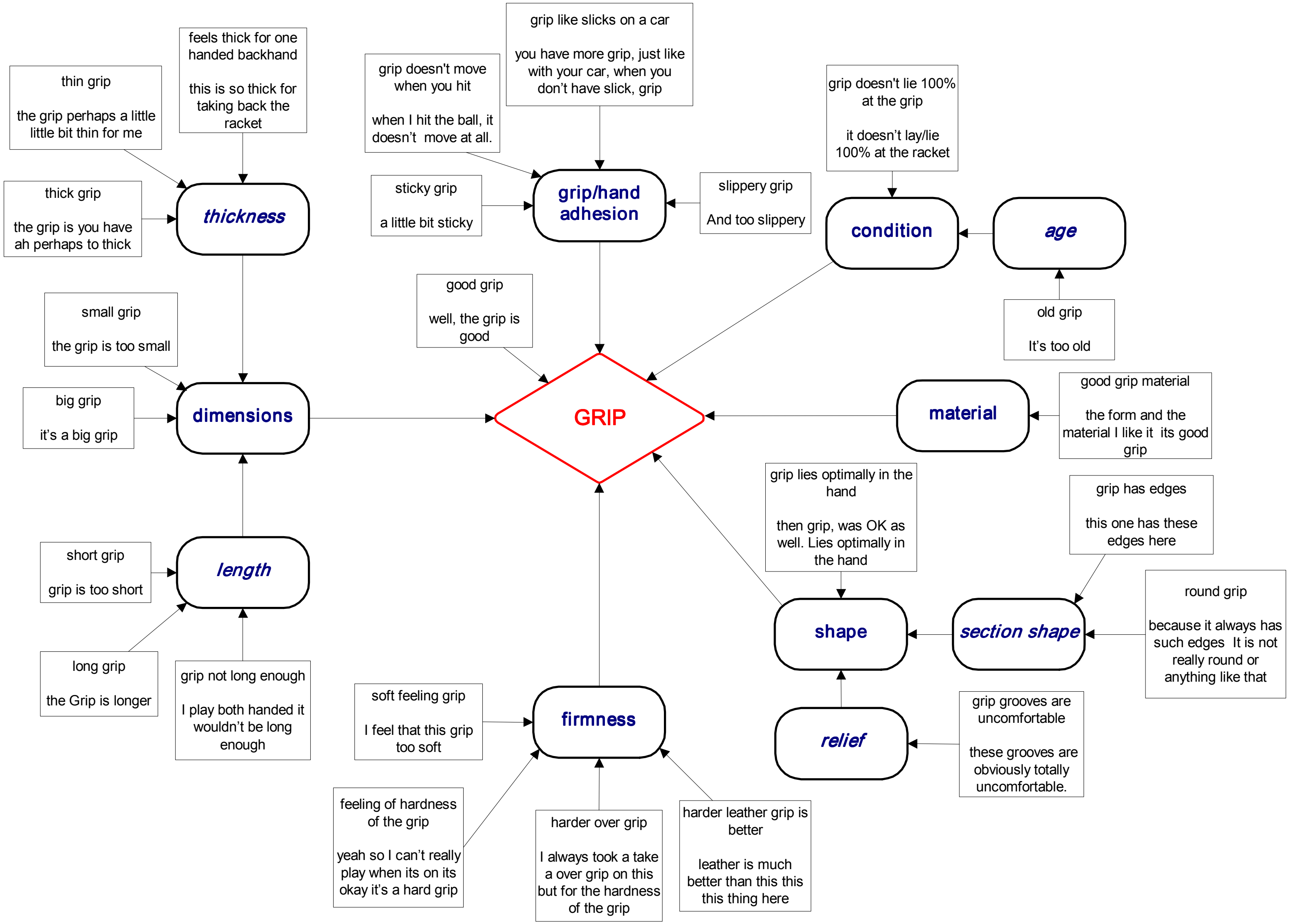


Figure 4.12 German map Grip cluster

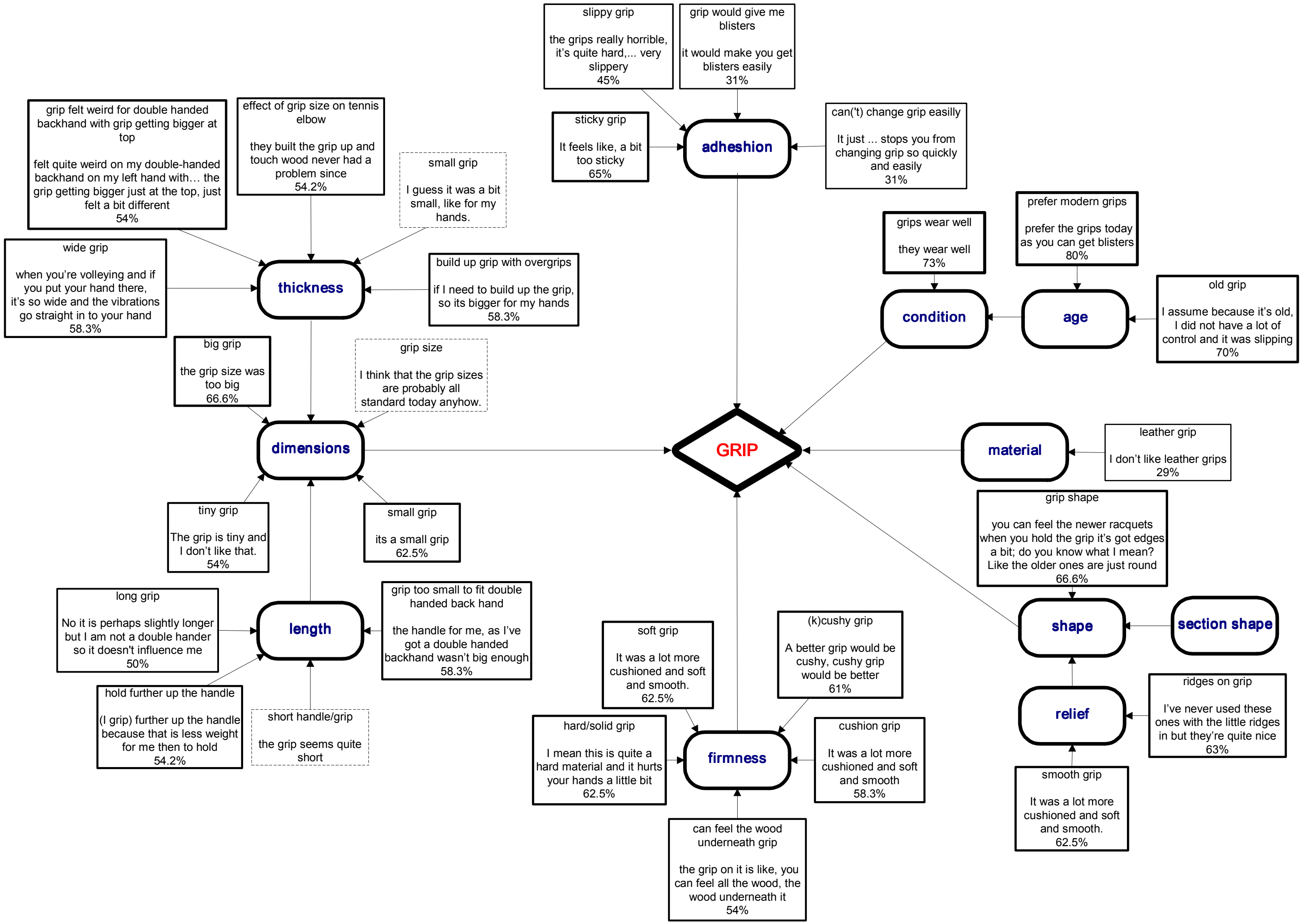


Figure 4.13 English map Grip cluster

The vocabulary with the highest percentile use associated with the cluster was that used in the ‘power/pace’ quotes (69%) and that used in the ‘flew/flies off the racket face’ quotes (63%); considerably higher than the vocabulary that was used in the ‘took effort to get power/pace’ quotes (45%). Percentage use data suggests players more commonly talk about racket power in terms of the end result, than in terms of the effort to achieve a particular result, and least often in terms of the reaction of the racket to a given input. As an example of the worth of using the model for feedback questionnaire development, approximately two thirds of players would be unfamiliar with thinking about racket power in the last context i.e. if a question about power is posed in terms of the reaction of the racket to a given input, two thirds of participants may get confused.

It was interesting to see the inclusion of the effects of a shock absorber on power in the English model. Clearly a shock absorber would have little influence on the actual coefficient of restitution of the racket, but it is conceivable that there is some significant link between the vibration response or sound of the racket and the perception of power. It is worth noting that a very low proportion of players recognised the vocabulary as something they might use themselves.

In both maps there are quite a number of interdependency relationships (7 in each map) between power and many other aspects of the racket suggesting that power is one of the central factors in racket perception, having some effect on many other racket characteristics, particularly when the high average relative importance rating is also considered.

4.6.5 Control

The ‘control’ cluster from the English and German feel maps (figure 4.16 and 4.17) also have a similar structure. Like the power cluster, in both maps the control cluster has a lot of interdependency links with the rest of the model, and a high average relative importance rating (67%) suggesting it is a group with a high level of influence on players’ perceptions of other aspects of feel. Additionally the group has a large number of nodes and sub-classifications since control is another racket quality that was commonly discussed at length in player interviews, to captivate players’ thoughts on differing aspects of control and subtleties in the associated vocabulary.

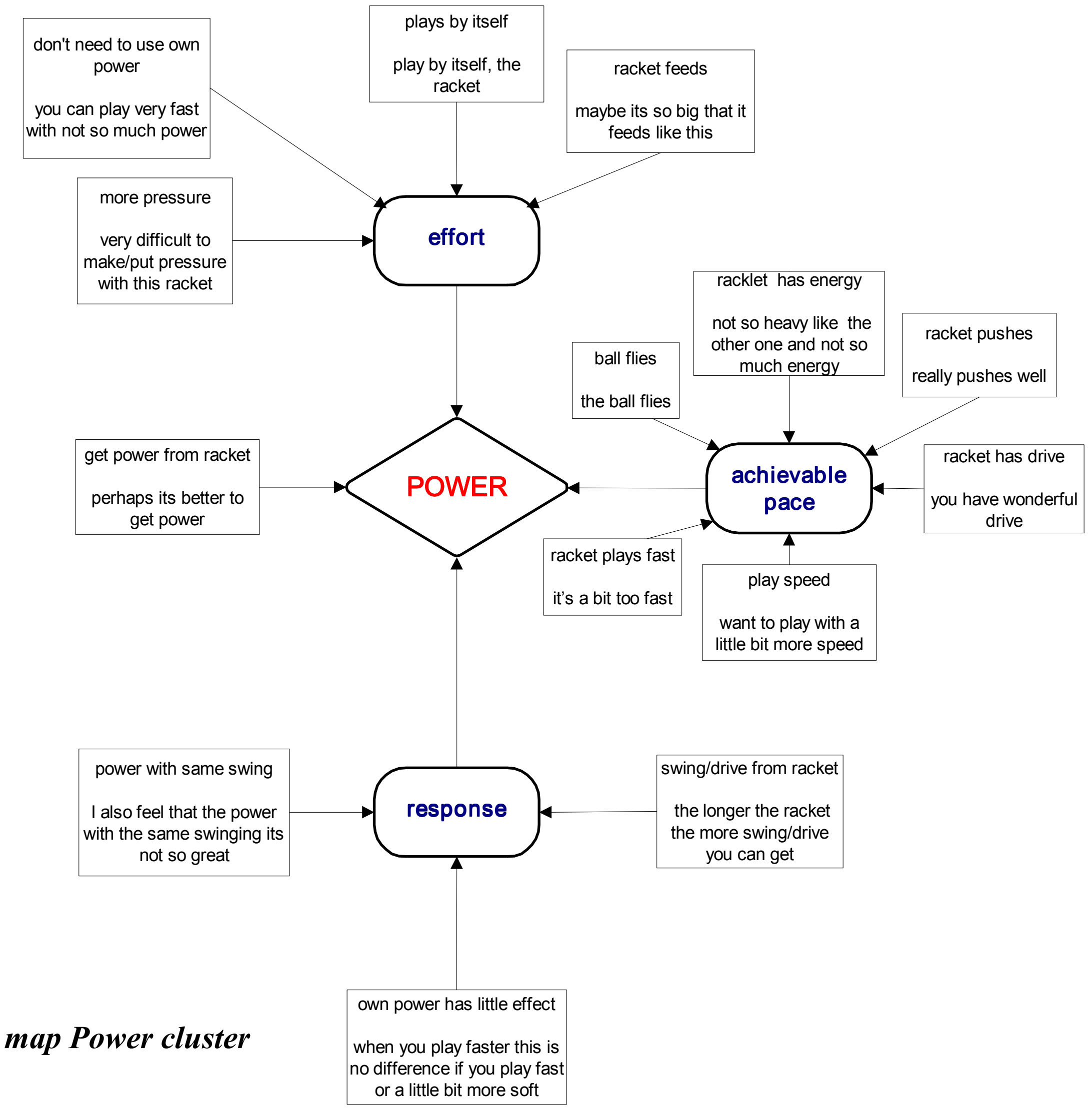


Figure 4.14 German map Power cluster

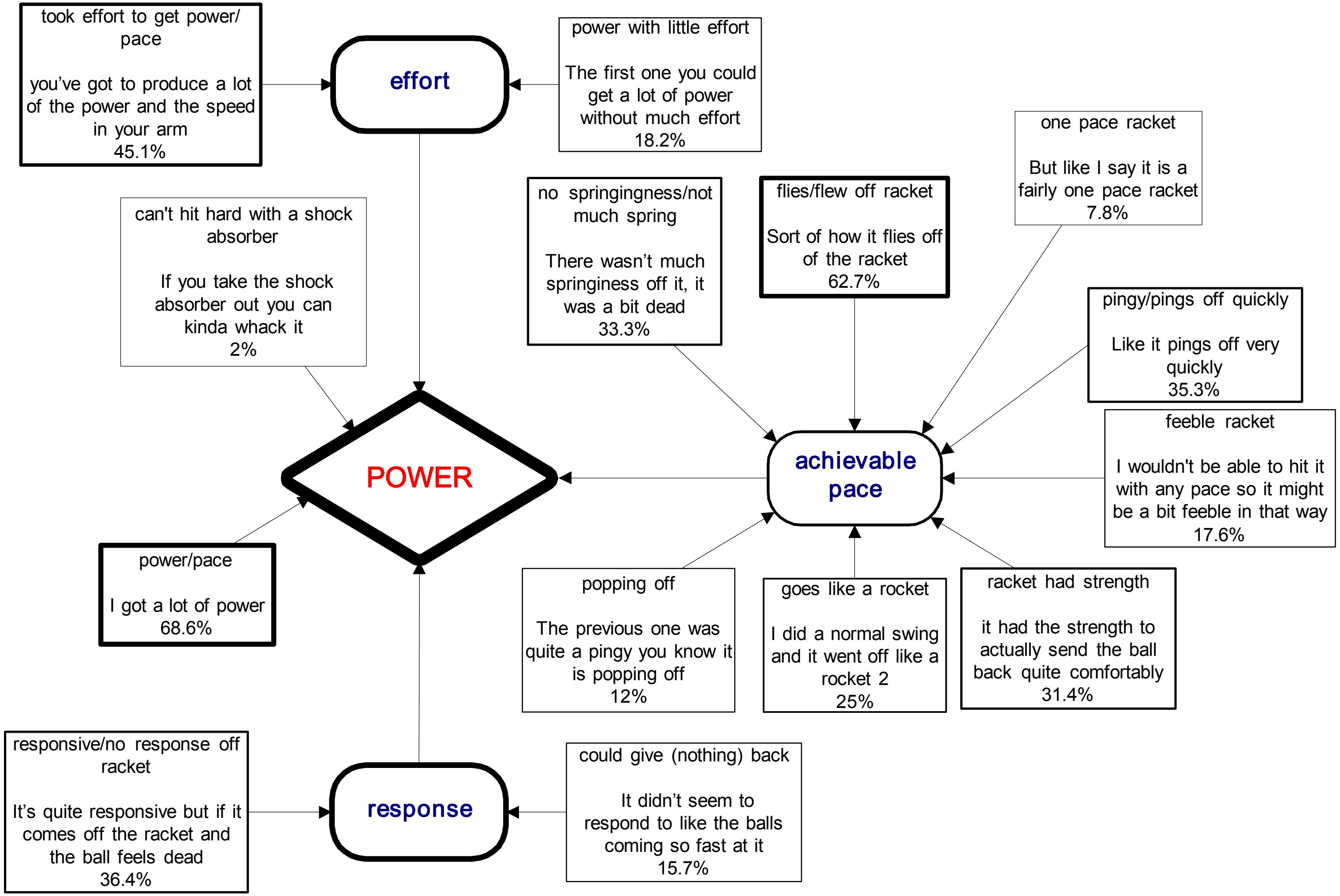


Figure 4.15 English map Power cluster

The ball control base theme indicates that approximately one third of players conceive of control in relation to ball trajectory outcome, much less than might be expected, whereas ball timing was referred to by about 75% of the sample, suggesting it is the feeling of impact that dictates to the player whether they have control over the ball or not rather than the ball trajectory. With a percentile use of 83% the node 'racket does what it wants' is the highest rated within the control cluster. It seems that players tend to most commonly refer to control in a negative sense i.e. a racket's lack of control. This might indicate that players do not expect a racket to improve upon their own level of accuracy, but are very aware when a racket restricts it in anyway. Players seem to view spin in a similar way with only small proportions of players commonly referring to it (27%) and most of the vocabulary relating to the difficulty in achieving spin i.e. the restrictions imposed by the racket rather than any racket qualities that improve the player's ability to generate spin.

The vocabulary with the highest percentile use associated with the cluster was that used in the 'difficult to time the ball' quotes (75%) and that used in the 'racket does what it wants' quotes (63%). The 'power without control' quotes had a surprisingly low percentile use (27%) although such high level vocabulary might be expected to be more commonly used. This might be explained by the context of the quote that may have lead to some confusion over the classification of the vocabulary. The quote could be considered as a reference associated with power rather than with control. With no data to support a reclassification of this node to the 'power' cluster it is difficult to justify such a decision. Further work with the online questionnaire would provide the data necessary to clarify this matter.

4.6.6 Feedback

In both maps 'feedback' (figures 4.18 and 4.19) is the largest of the clusters and ties up with many other areas of the model via interdependency links indicating that it is another key group and as might be expected has a strong average relative importance rating (56%). As with many of the groups there are several similarities between the clusters from each map, however, in this case there are also a larger number of discrepancies than in the other cluster comparisons.

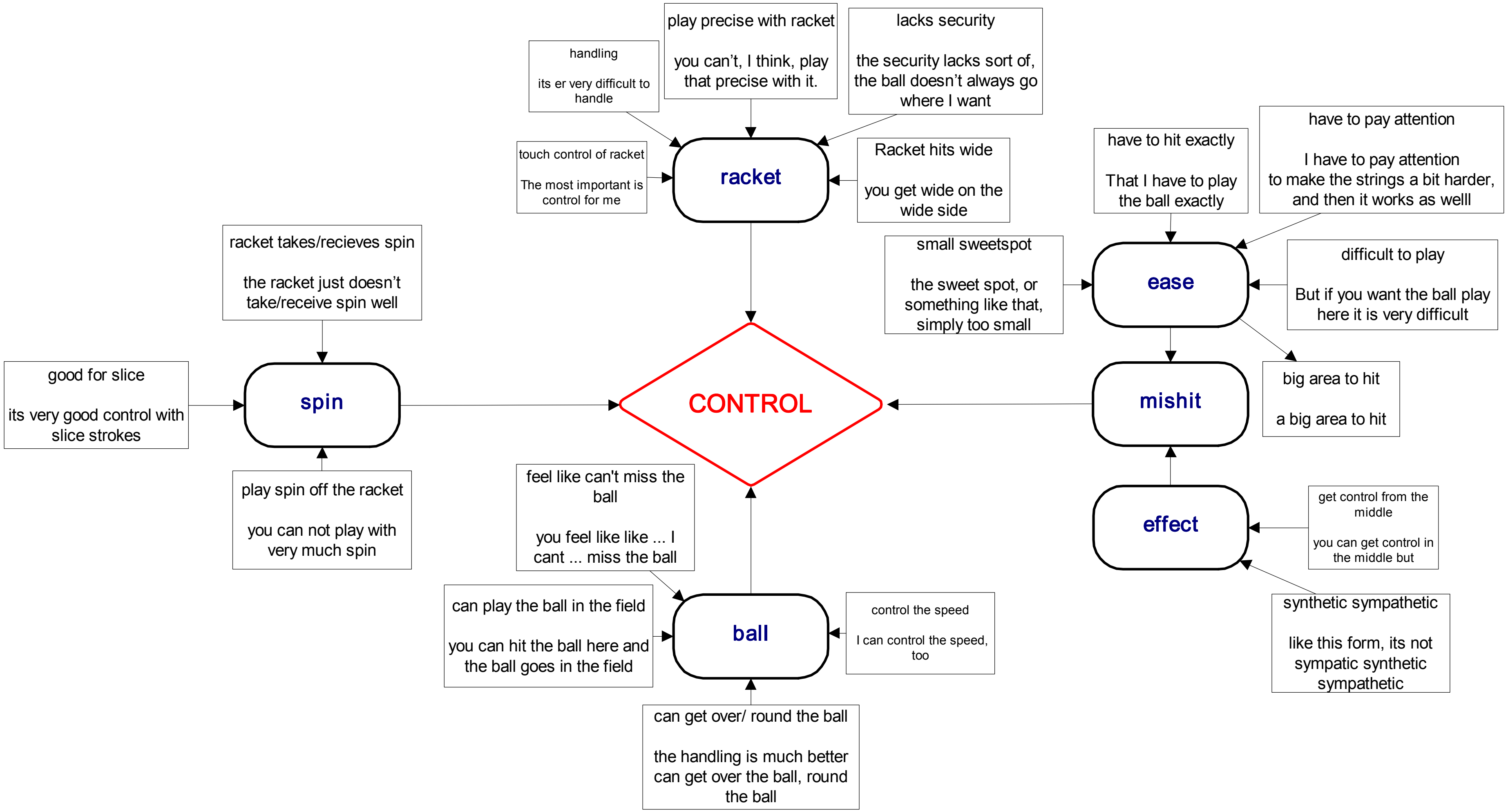


Figure 4.16 German map Control cluster

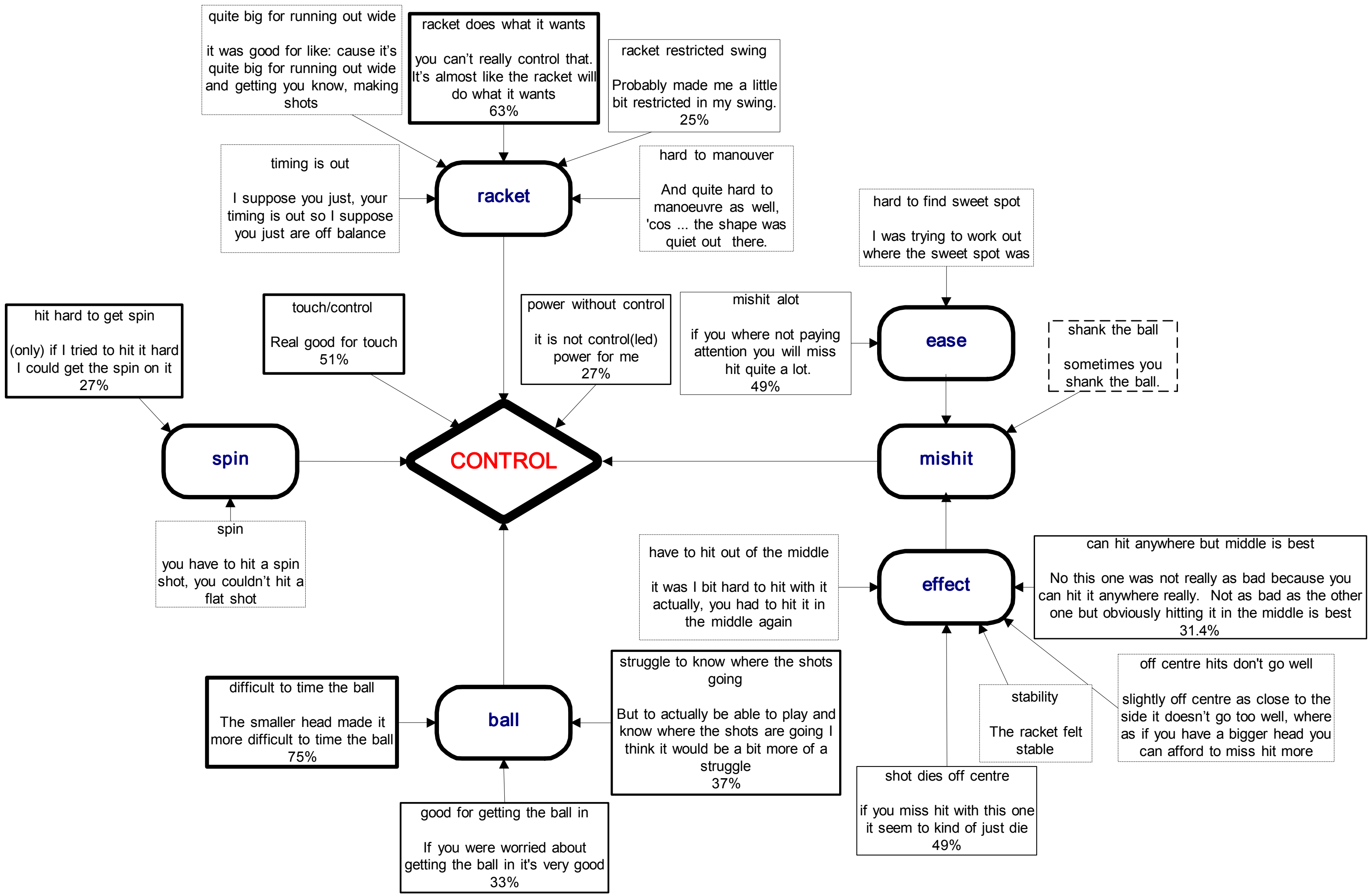


Figure 4.17 English map Control cluster

The ‘grip’ sub theme in the German map is not present in the English map, but there are interdependency links that imply a similar link and reference to ‘comfort of the grip’. It seems that the English players indicated that there was a relationship without specifically expressing the link in reference to feedback. Instead the primary emphasis was on the grip and its associated affects on the feedback. The interview testing was deemed to be exhaustive but it is conceivable that, since it seems likely that this link exists in both maps and very similar vocabulary is already evident, although this element is clearly not usually explicitly referred to in the community additional English interview testing would eventually divulge more explicit vocabulary in reference to this area.

A more prominent difference is the additional ‘stroke/kinaesthetic’ subtheme in the German map. This suggests that the German players were more aware of their ability to perceive the racket head position. This may be a result of differing coaching methods and emphasis.

It is interesting to note that a high proportion of players conceive of the racket in terms of their ability to feel the ball through it (‘heavy ball’ 80%, ‘feel on the ball’ 67%). Few would be aware that they are only experiencing the consequences of an interaction too quick for them to assess. The relatively high percentile use of vocabulary relating to feedback (‘strange to play with’ 61%, ‘can get used to it’ 55%) is to be expected given that players can often be seen, as was the case with Pete Sampras and his Wilson Pro Staff, becoming attached to a specific racket type, and the bulk of the node titles (5 of 7) relate to unfamiliarity. In effect, it is more likely that a racket will be notably unfamiliar, rather than remarkably similar to a player’s own racket.

It is interesting to see more than half of players referring to a ‘nice connection’ (53%), a phrase that in itself offers little description of any particular phenomenon. It is likely that the phrase is commonly used since its indistinct nature can encompass a variety of stimulus that make up an overall perception of racket feedback. It is possible that comfort related vocabulary (‘comfortable racket’ 14%, ‘comfortable grip’ 18%) has low percentile use for a similar reason, in as far as comfort could be either encompassed by broader, less specific vocabulary, such as nice connection, good sense in the hand etc. or broken into more specific elements, such as vibration, unfamiliar racket etc. As with familiarity, much of the vocabulary is negative, relating to lack of comfort, which could suggest that a racket is assumed to be comfortable, and players only really remark on rackets that are notably uncomfortable.

4.6.7 Racket Dimensions

Racket dimensions is a large cluster with similar structure in both maps (figure 4.20 and 4.21). It seems, as might be expected, that players most commonly refer to racket dimensions in terms of the basic dimensions of width (‘width of racket’ 75%) and length (‘racket length’ 83%).

With frame section nodes with percentile use values of 60% or more, it was surprising to see that ‘thin beam’ (20%) and bulky frame (18%) had such a low percentile use. Referring to the thickness of the frame as a beam is an unusual and potentially misleading or confusing use of the phrase which could explain the low use in this case. If the similar ‘bulky frame’ node is considered, which is perhaps a more familiar and descriptive phrase but with equally low percentile use, it seems there must be some additional reason for the lower percentile use. It is difficult to understand these figures when other, very similar nodes, such as ‘chunky frame’ have much higher values. One possible explanation is that these phrases are used exclusively; players either use one or the other and participants selected the vocabulary they considered to be most appropriate or descriptive. Whilst they might still understand the meaning of the other phrases they would not be words they would commonly use themselves.

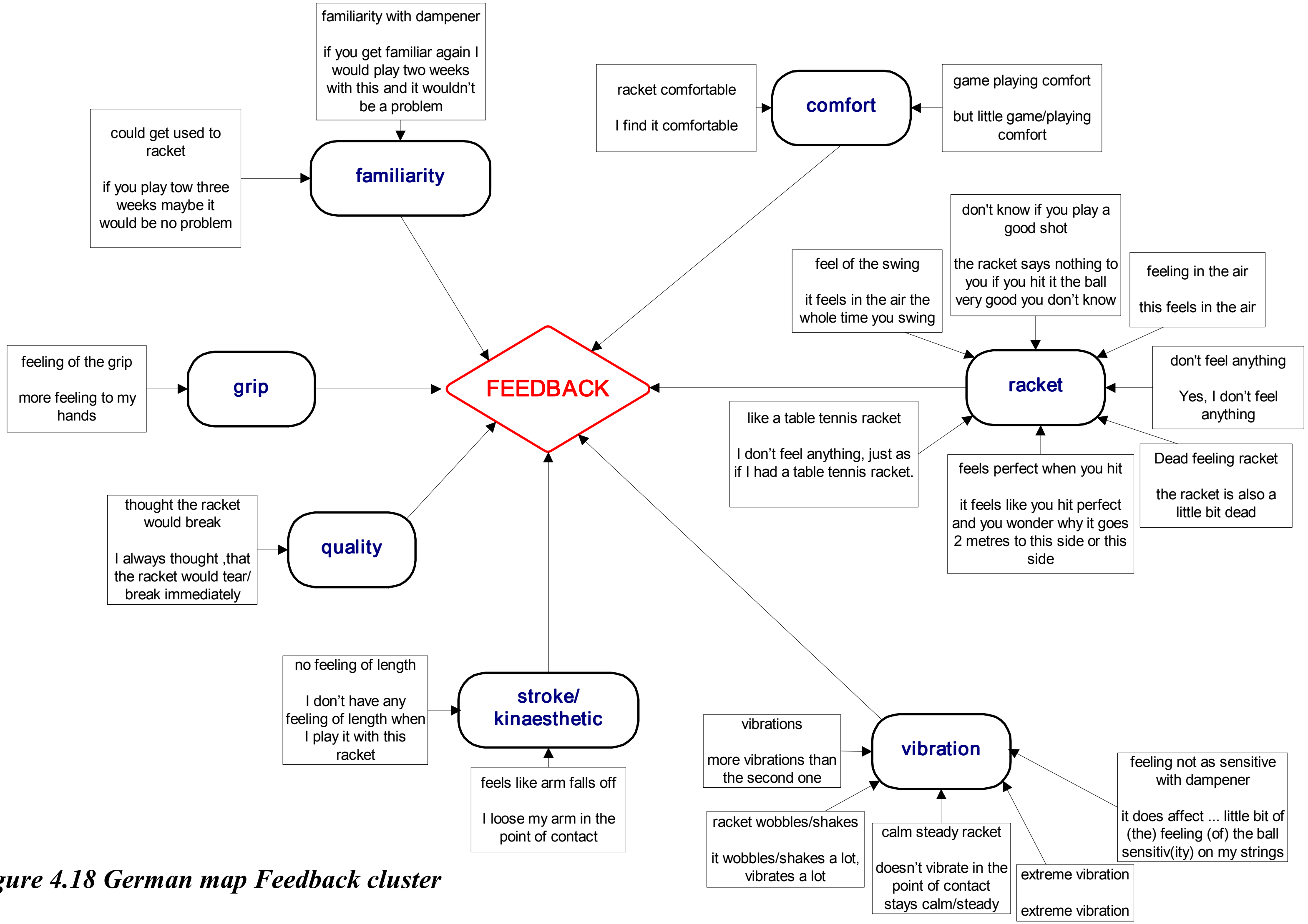


Figure 4.18 German map Feedback cluster

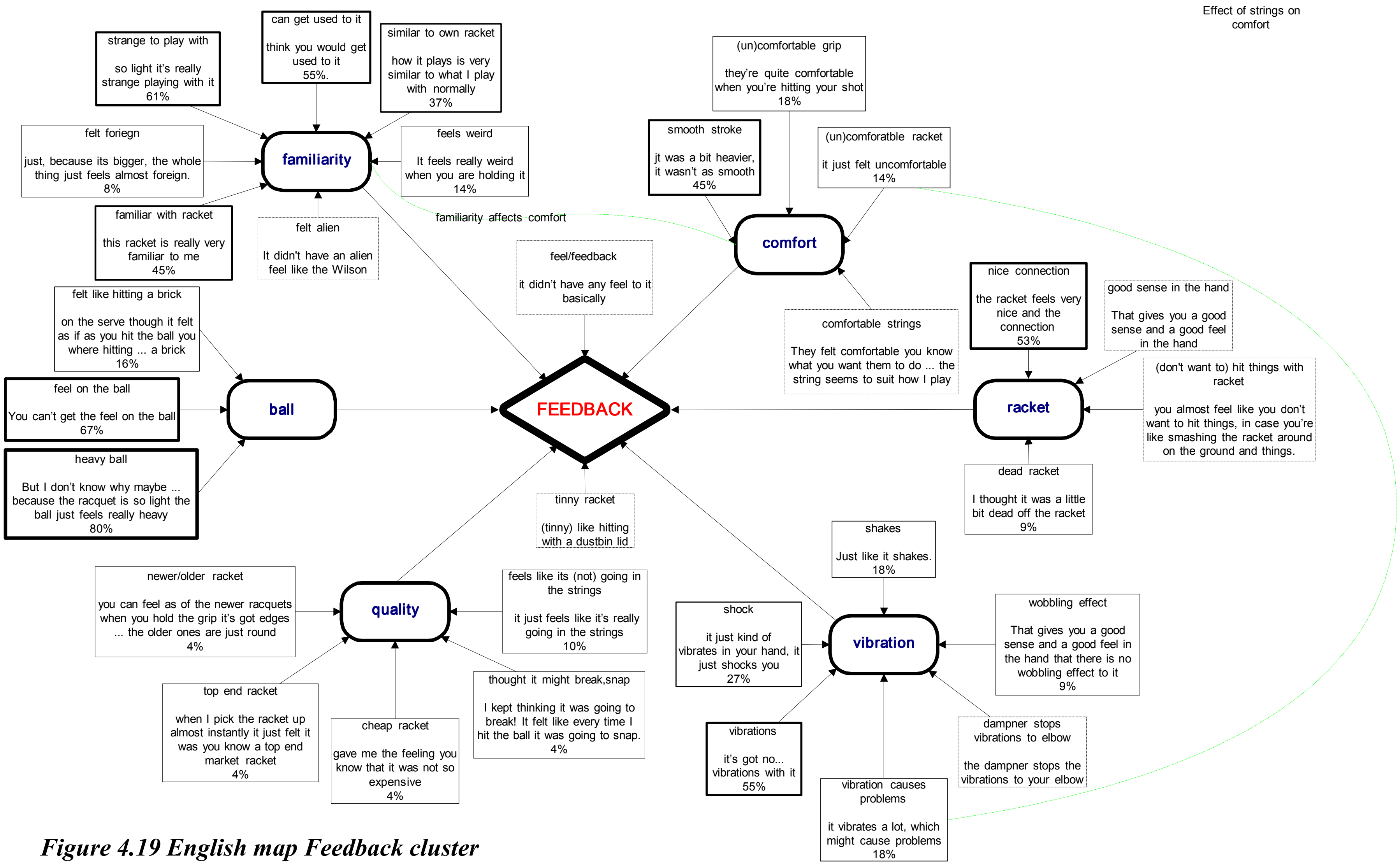


Figure 4.19 English map Feedback cluster

In both the English and German maps there are a high number of interdependency links (9 and 5 respectively) to other areas of the map indicating the influence of racket dimensions on players overall perception of racket feel. This is not at all surprising given that the dimensions of the racket can dramatically change many of it properties including its appearance, swing ease and performance. Particularly interesting is the effect of the racket proportions on control and feedback, indicated by the interdependency links in both maps. The links show how both groups identified the affect of having a larger distance between the hand and the contact point on the racket, an indication of kinaesthetic awareness, although it is not identified specifically as such.

4.6.8 Flexibility

The ‘flexibility’ cluster again has a matching structure in both maps (figures 4.22 and 4.23). It is interesting to note that the relative importance of flexibility (30%) indicated in the English map is not as high as some of the other clusters, but there are 6 interdependency links suggesting that, although players don’t consider this to be a particularly important factor of racket perception in itself, it does have implications for the perception of other areas of racket perception.

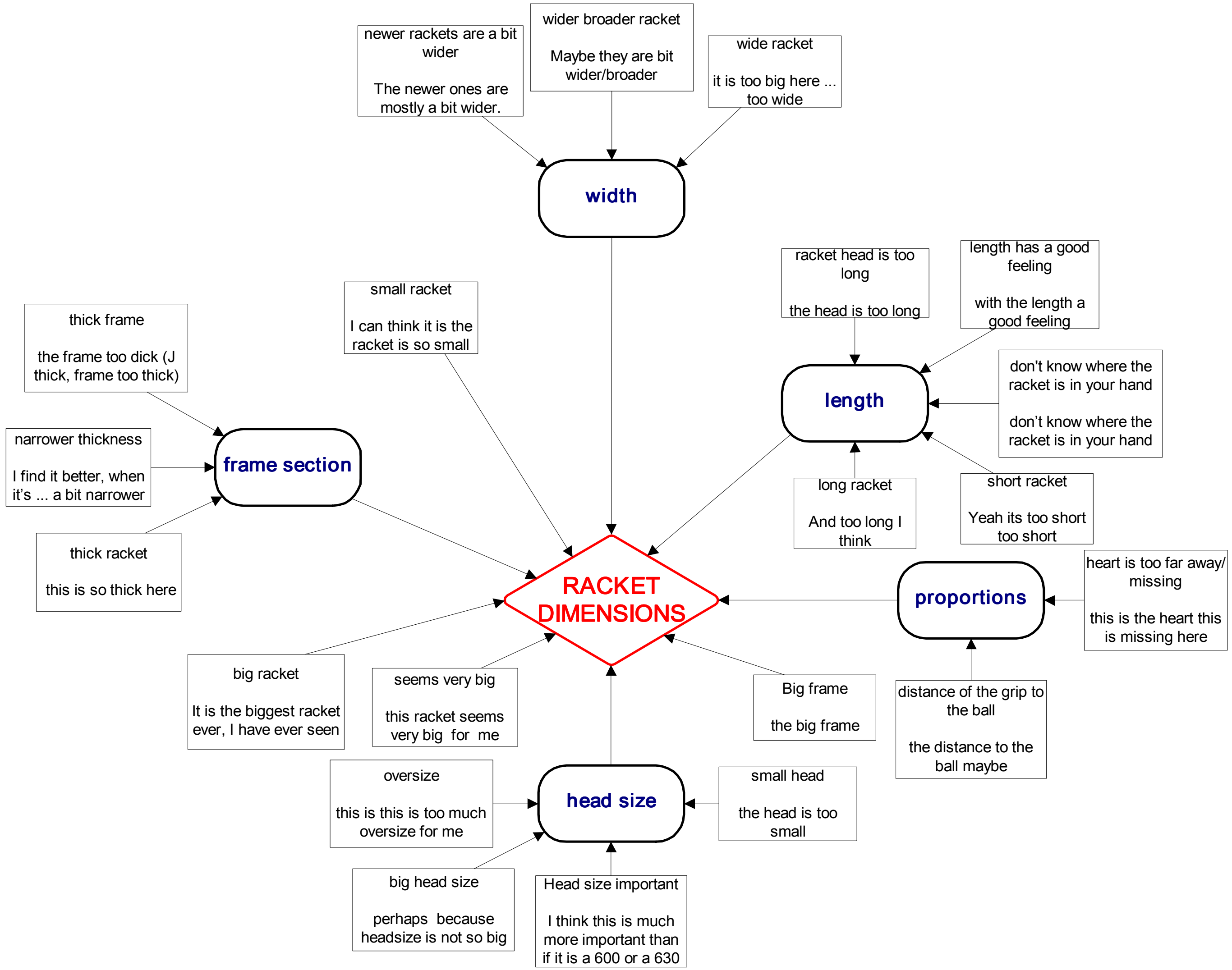


Figure 4.20 German map Racket Dimensions cluster

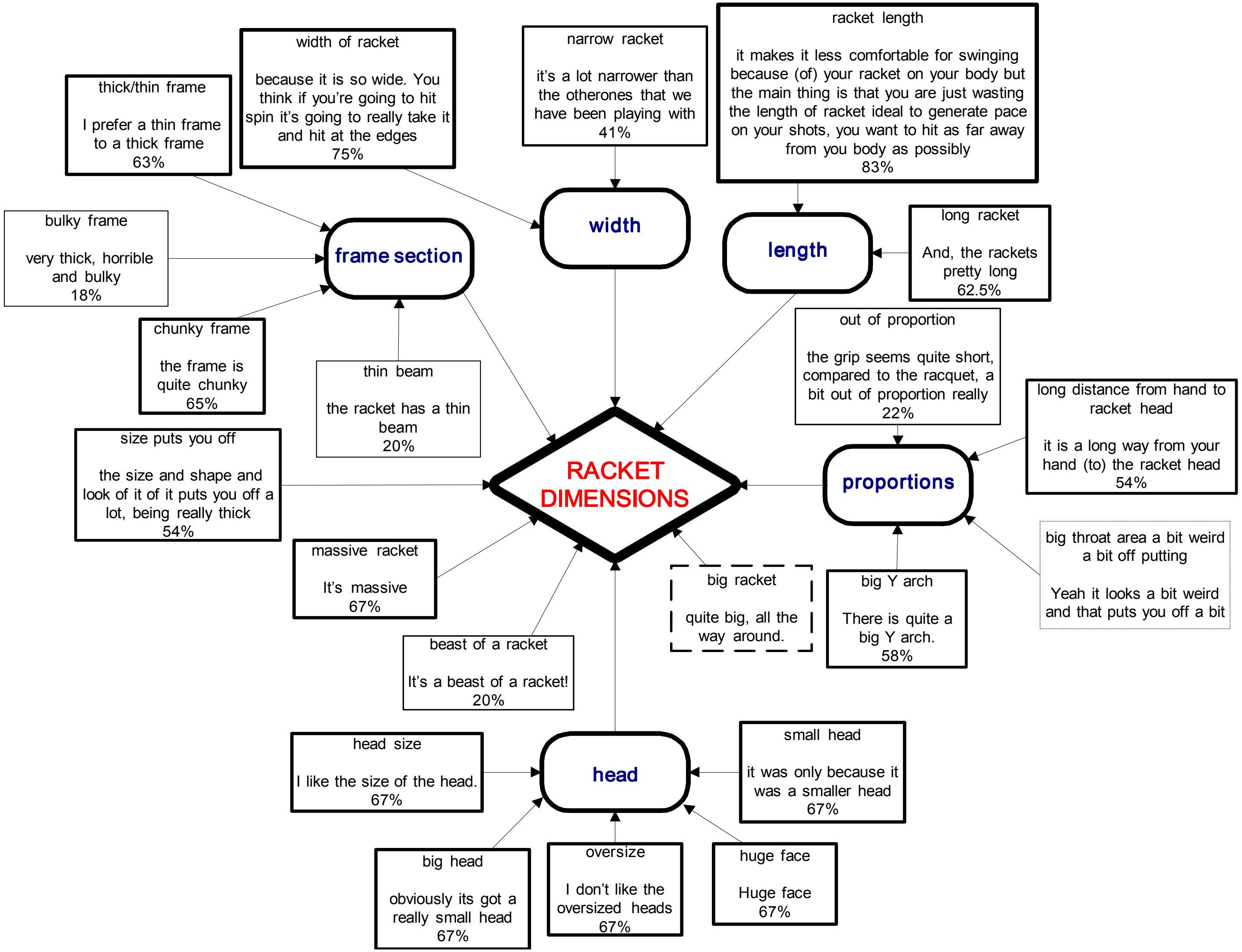


Figure 4.21 English map Racket Dimensions cluster

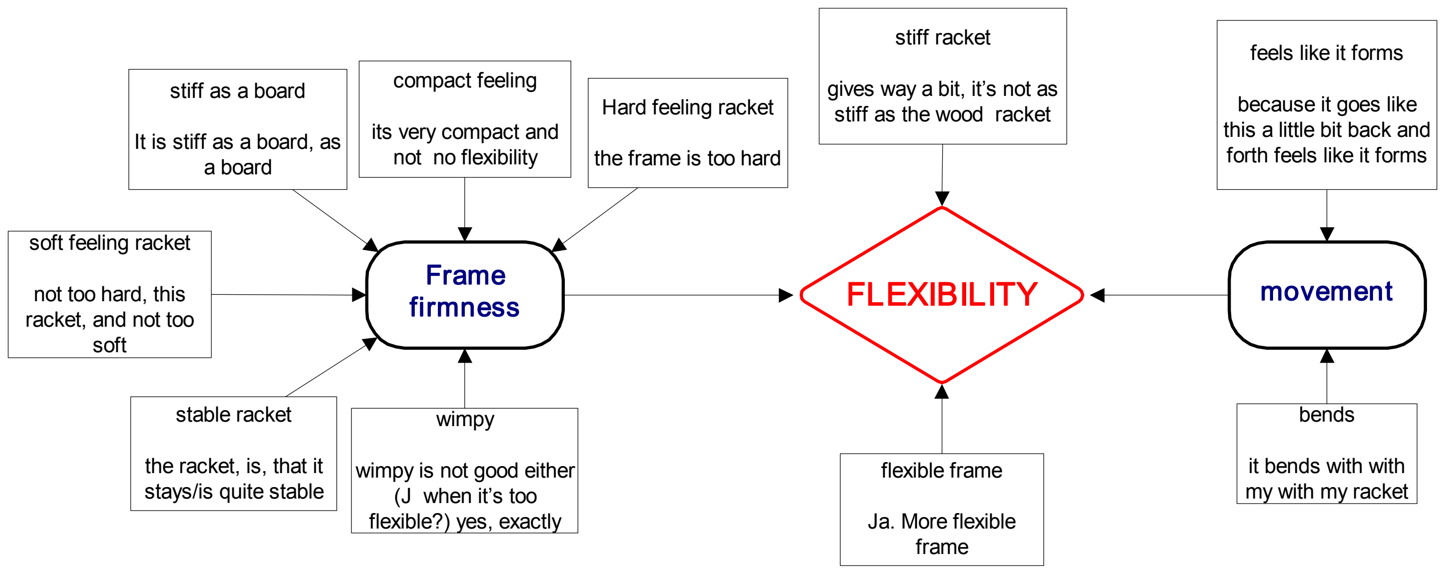


Figure 4.22 German map Flexibility cluster

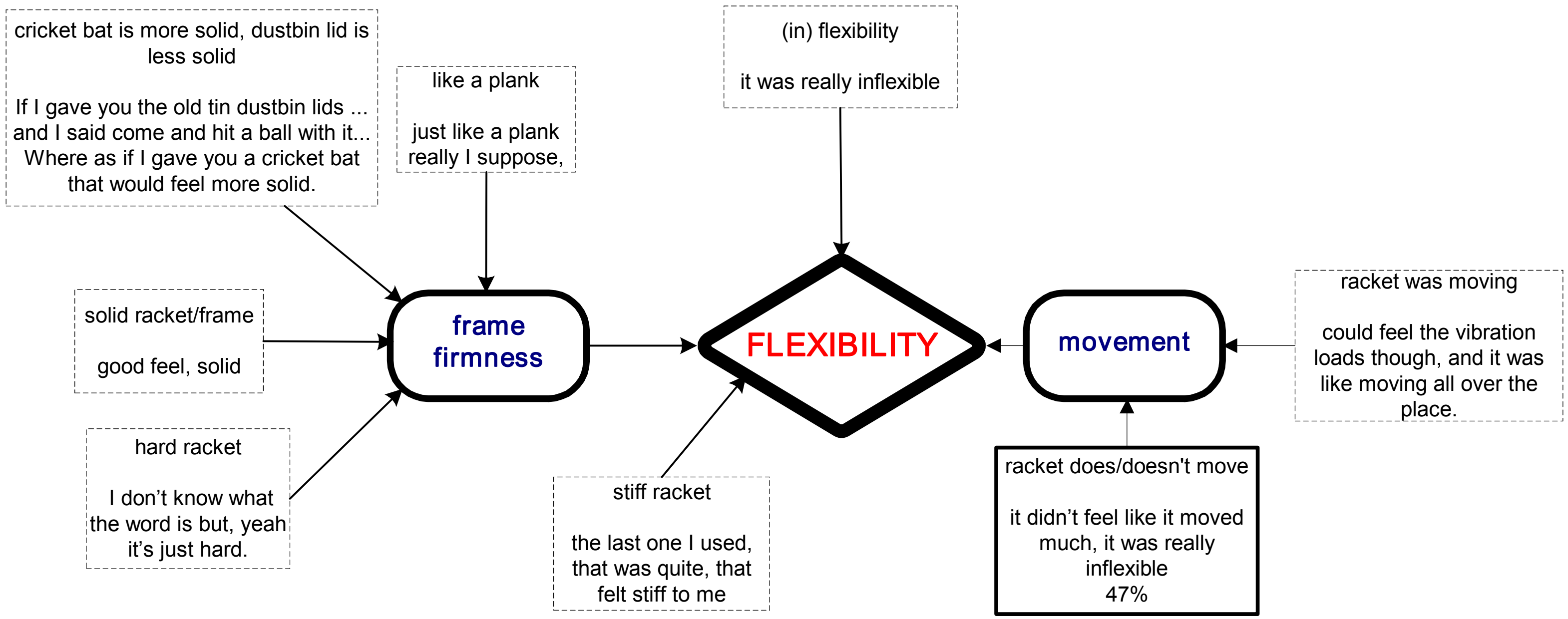


Figure 4.23 English map Flexibility cluster

4.6.9 Anticipated Use

The 'anticipated use' cluster has a matching structure in the English and German maps (figure 4.24 and 4.25), with a few links of interdependency (3 in the English and 2 in the German). The cluster is well established in both maps having a considerable number of nodes and base themes associated with the general dimension itself in each case. The low instances of interdependency and their description suggest, as might be expected, that this area of perception does not have as strong an influence on players overall perception of a racket as other areas. However it interesting to observe that, of the percentile vocabulary use data that exists for this cluster for all 3 base themes, all nodes are rated over 50% and 4 of the 6 rated node have values over 70%. It seems that whilst the cluster might not have much influence over other areas of the map, players are very familiar with it and use an established common vocabulary associated with it.

4.6.10 Cosmetics

The English and German 'cosmetics' clusters (figures 4.26 and 4.27) are similar in structure, the most prominent difference being the absence of a 'brand' sub theme in the German model, and of an 'iconic' sub theme in the English model; referring to cosmetics that draw visual similarities to iconic players' rackets. Since the rest of the German cluster is very similar to the English one it seems there may be a greater cultural emphasis on iconic players in Germany and perhaps a greater emphasis on brand awareness in England. With this considered it is worth noting that the English 'brand' sub theme has only one node associated with it, although this was not addressed in the web questionnaire this may be indicative of a lower percentile use or importance. The sample groups on which both feel maps are based both consist of players of relatively high ability level, and a more prominent influence of both branding and similarities with iconic payers' rackets might be expected if the procedure were expanded to include lower level players since this is the demographic that these forms of marketing are most commonly targeted at.

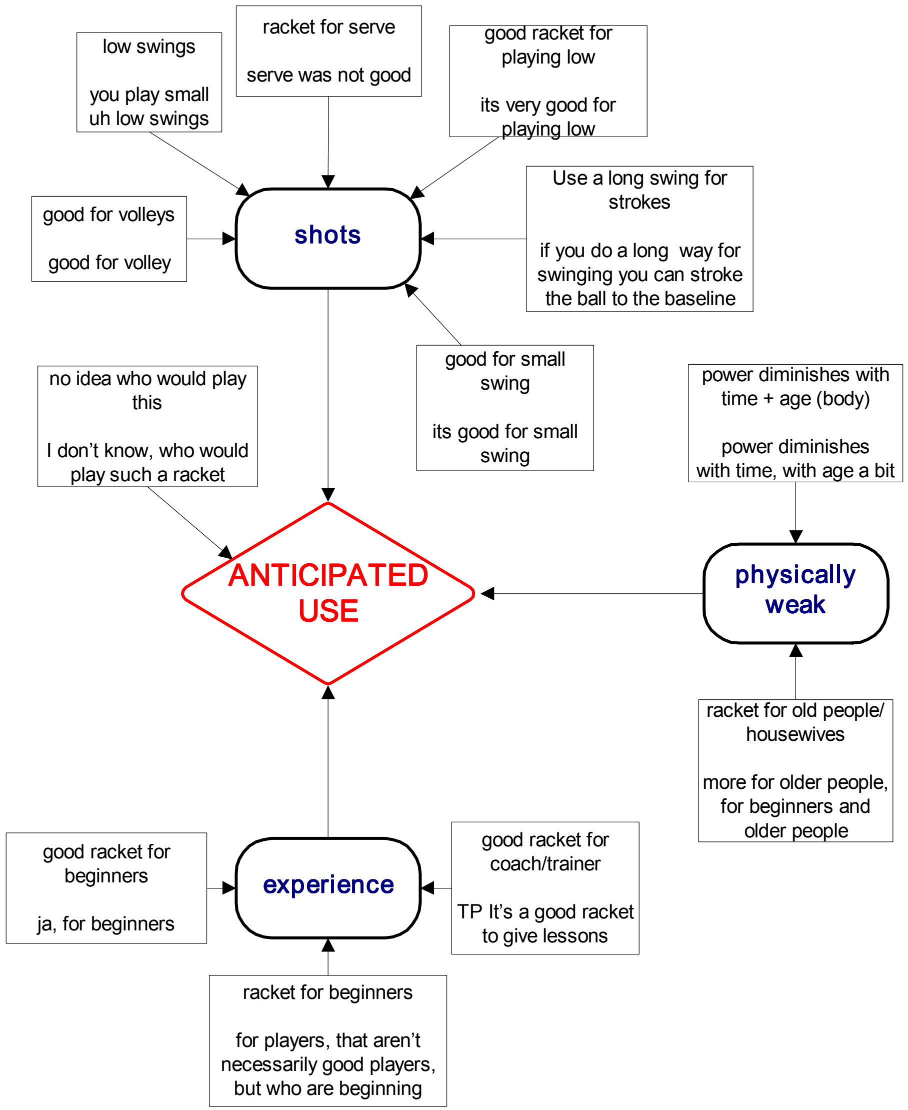


Figure 4.24 German map Anticipated Use cluster

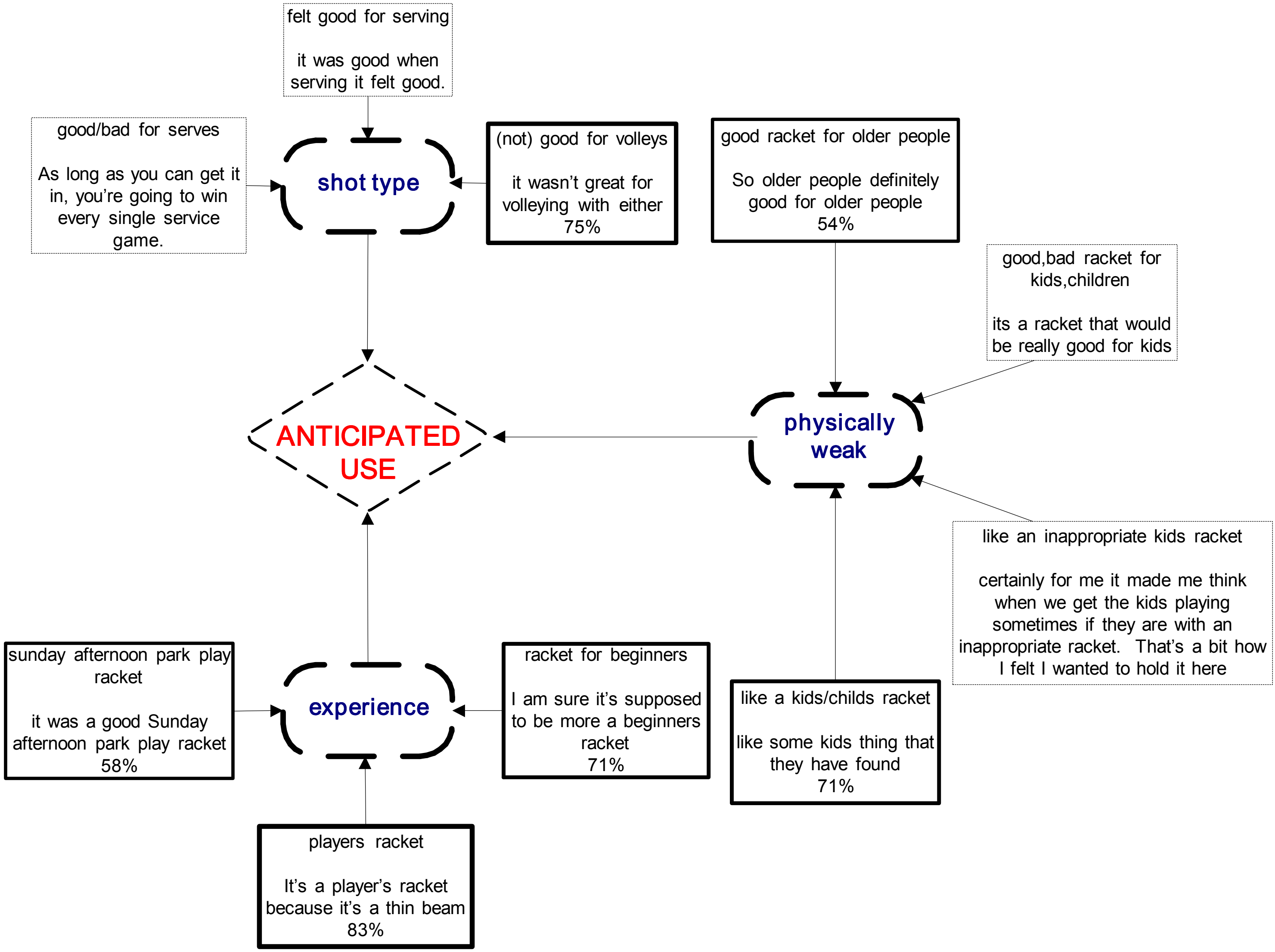


Figure 4.25 English map Anticipated Use cluster

The ‘cosmetics’ cluster is fairly large in both models with many nodes (English = 20, German = 33), base and sub themes but has few interdependency links. This suggests that, although certainly a significant attribute of the racket, cosmetics have little influence on the players’ perception of other characteristics of the racket. If the sample group is once again considered, it is conceivable that racket cosmetics might have more influence over the perceptions of other racket characteristics in lower level players.

The lower number of interdependencies found in this cluster meant that it was not prioritised for the online questionnaire and as result very little percentile use or relative importance data exists at present.

4.6.11 Inertia Properties

The most obvious difference between the inertia properties cluster in the English and German maps (figure 4.28 and 4.29) is with the swing ease base theme. The English map has 2 nodes associated with this base theme, whereas in the German map they are entirely absent. This might suggest that German players are less aware of its influence or that again, some difficulties were experiences with the language barrier. However it is hard to ascertain how commonly English players make reference to swing ease with no supporting data. It is conceivable that one or two unique or particularly insightful players made comments in relation to this element. Additional German interview testing could eventually divulge the same information, particularly when the relatively diverse English sample is compared with the more limited German participant selection.

Interestingly the head heavy node (82%) is the highest rated within this cluster, and head light (18%) is one of the lowest. This is surprising since might seem logical to expect what is essentially opposite terms for the same characteristic to be rated similarly. The higher value associated with handle heavy (41%) suggests that players are more comfortable making reference to where the weight is felt rather than its absence.

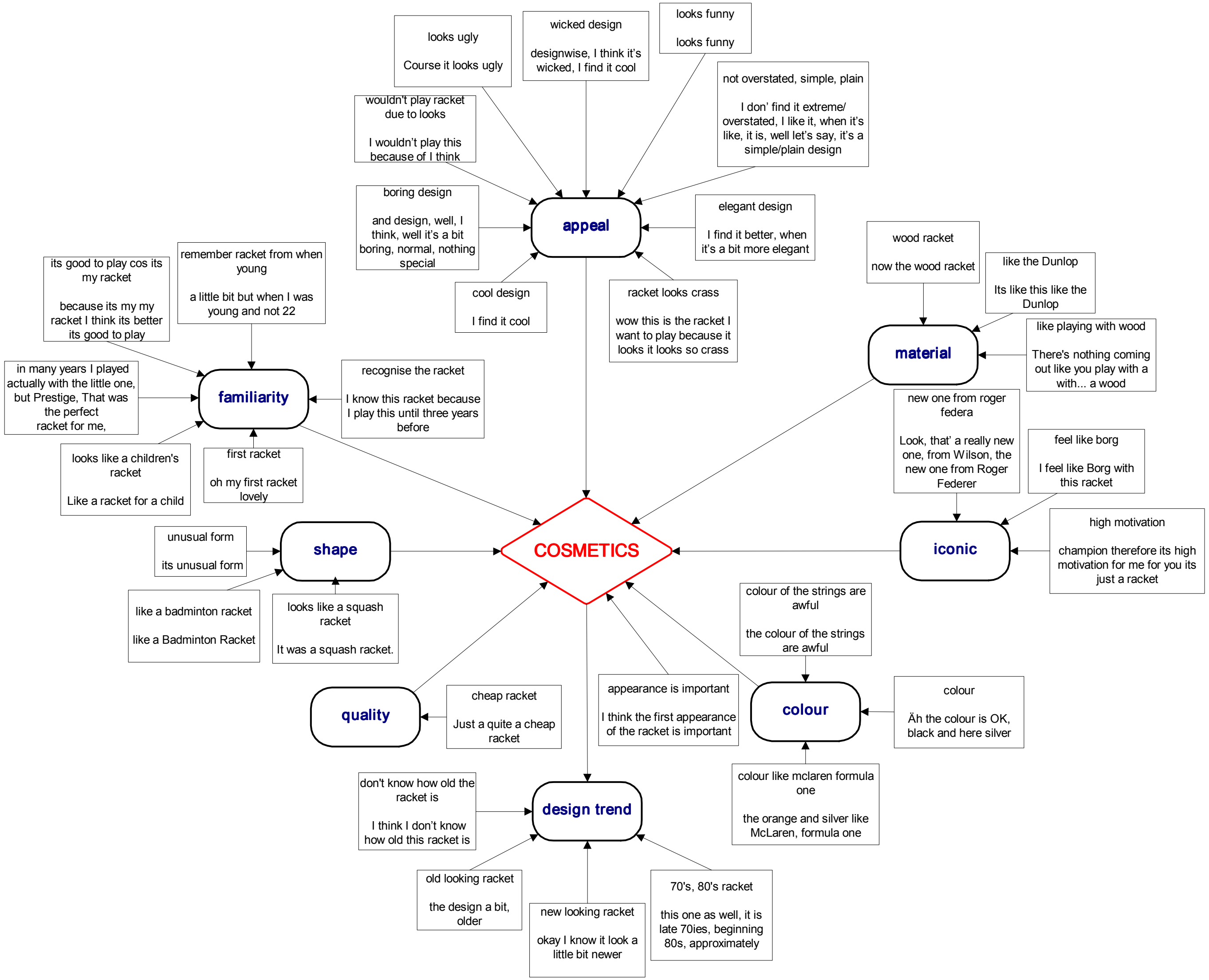


Figure 4.26 German map Cosmetic cluster

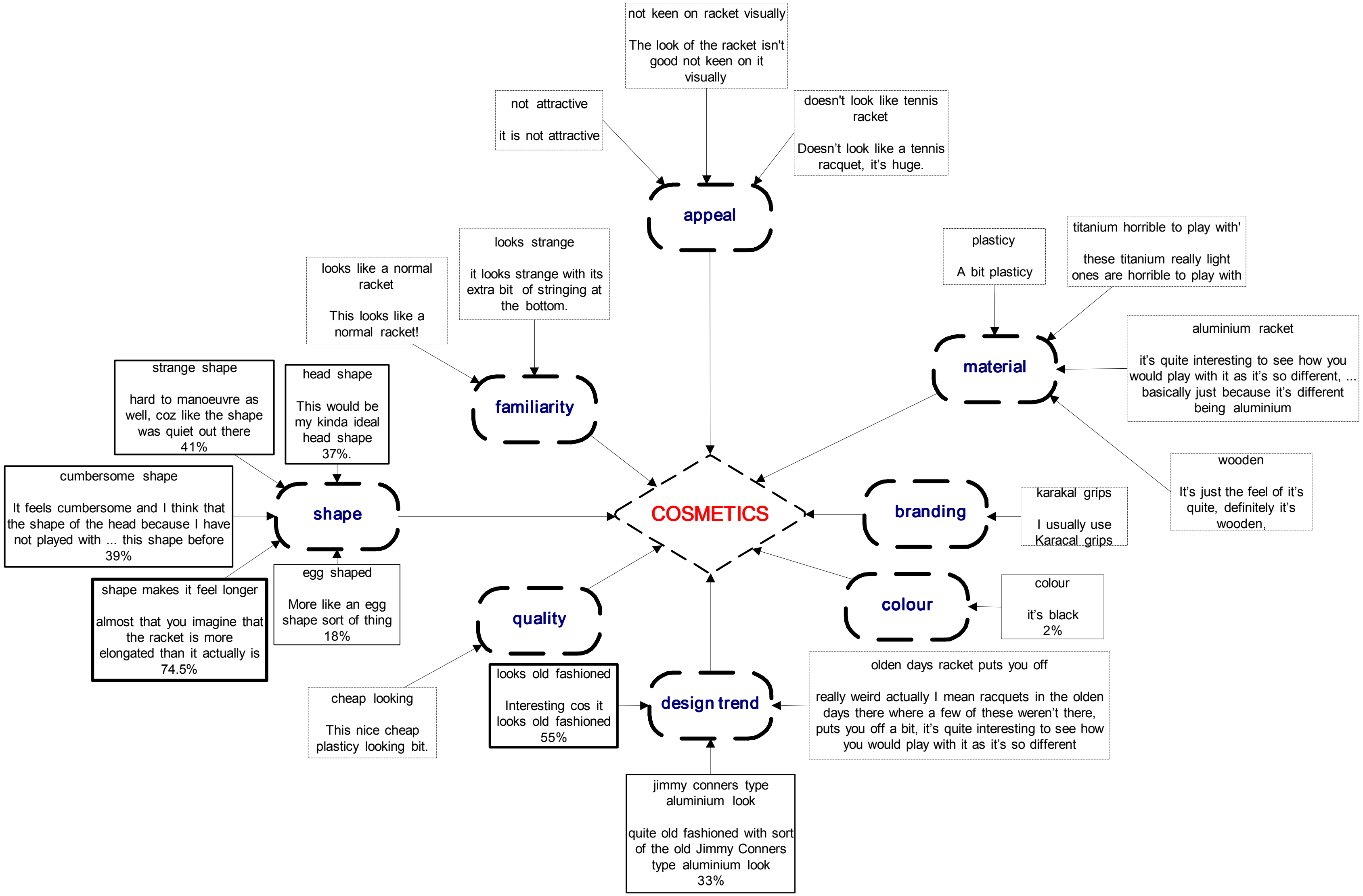


Figure 4.27 English map Cosmetic cluster

4.6.12 Physiological Effect

The ‘physiological effect’ clusters in the English and German maps have a matching structure. Neither are big clusters and have a limited number of interdependency links. Although there are only 3 interdependency links in the English map, it is more poignant to note that no links exist in the German map at all. It seems that whilst the German players were able to identify a racket that would have some physiological effect on fatigue or injury, unlike the English players, they did not seem to diagnose the cause. This is not to say that they were necessarily unable to understand why they experienced such effects, merely that they were not inclined to comment on it, which may be due to a number of reasons. They might, for example, believe the cause to be too obvious to be worth stating, or may have already made reference to the qualities of the racket that contribute to the effect and felt it unnecessary to repeat them in the context of each and every issue.

The high relative importance of the sub themes of fatigue (67%) and injury (84%) cluster indicated in the English map confirms that this is an important cluster in spite of its limited influence on the perception of the racket as a whole.

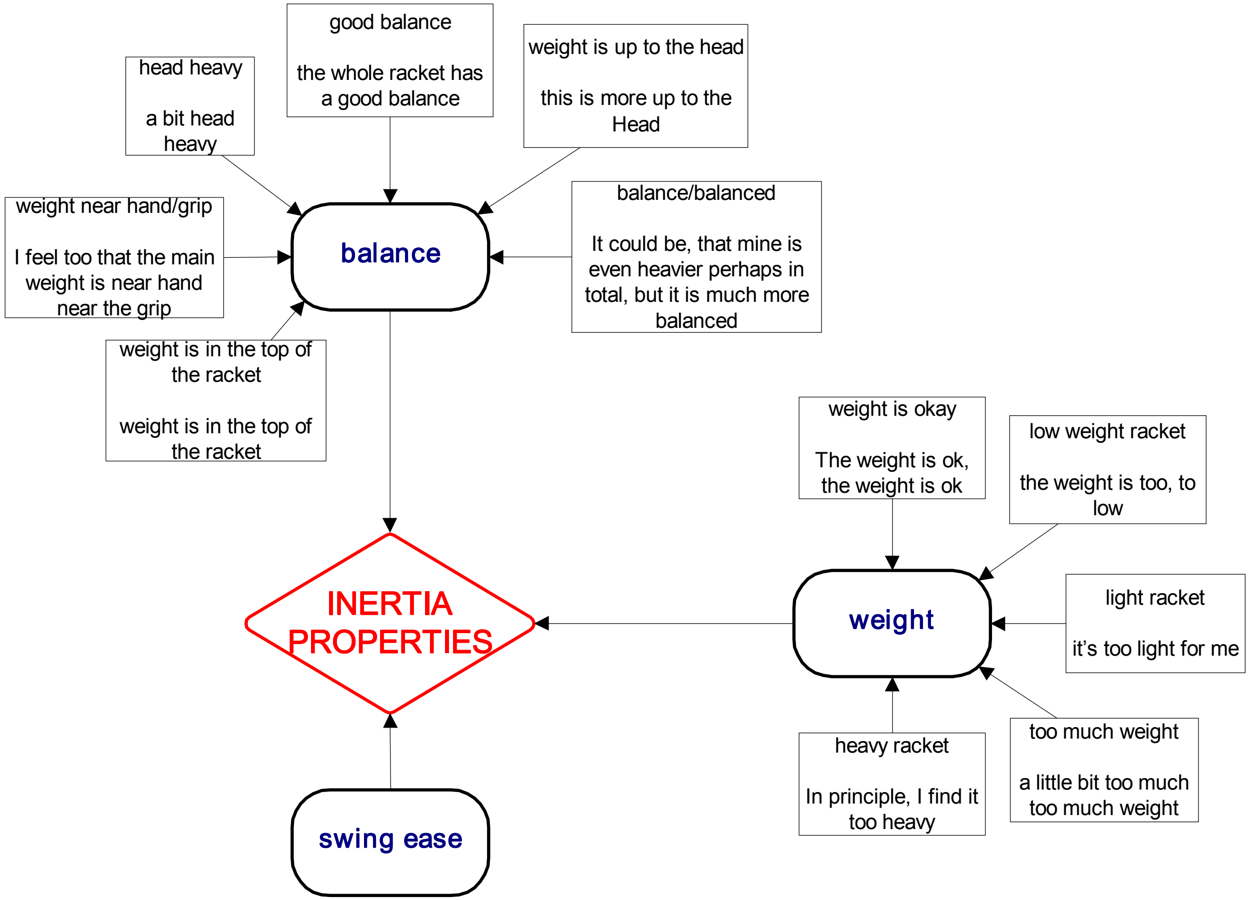


Figure 4.28 German map Inertia Properties cluster

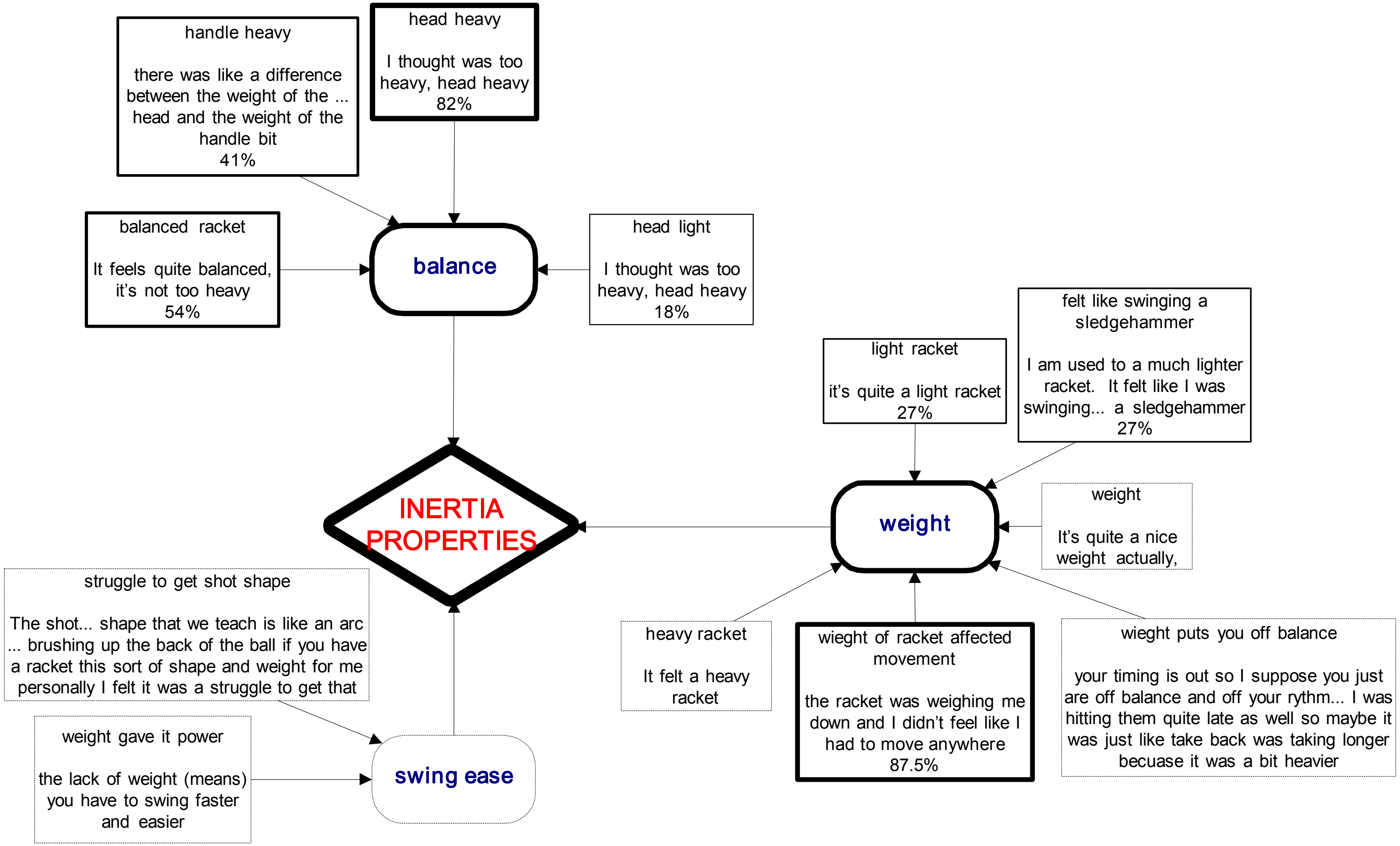


Figure 4.29 English map Inertia Properties cluster

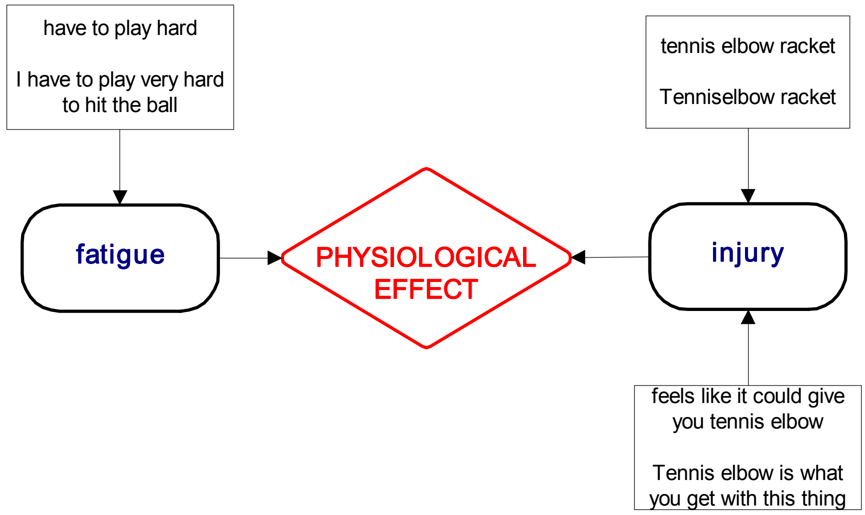


Figure 4.30 German map Physiological Effect cluster

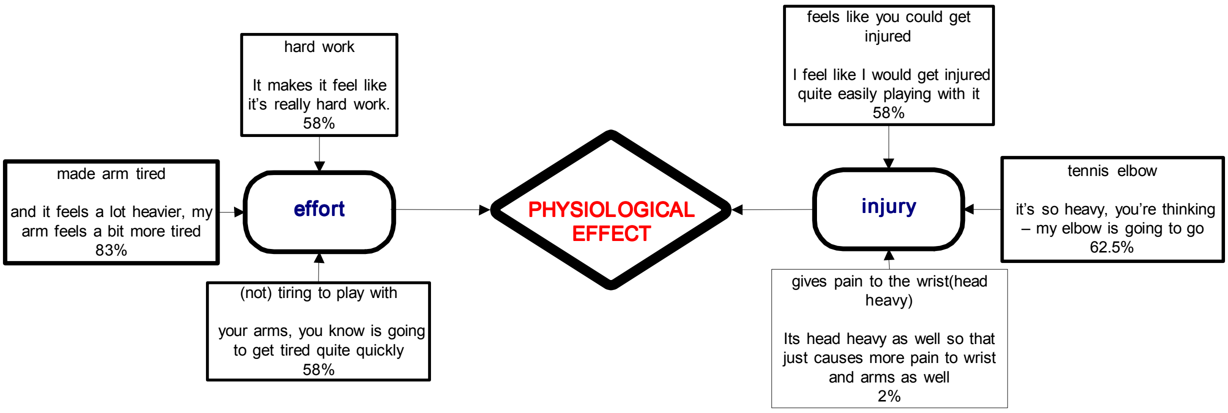


Figure 4.31 English map Physiological Effect cluster

4.6.13 String Bed

The 'string bed' cluster is the most different when comparing the two maps (figures 4.32 and 4.33). The 'pattern' and 'tension' base themes are present in both maps, but whilst the English map has considerably fewer nodes (8 in the English versus 15 in the German), there are a number of further base and sub themes that are not present in the much simpler, but better populated version from the German map. The bulk of these themes appear to be based on more technical information about the string bed specifically the string gauge, string type, string bed length, age and wear on the strings. This seems to be a persistent theme throughout the German map, where players have less focus on the finer subtleties and technicalities of each characteristic cluster. This might be attributed to differing coaching styles and cultures, or possibly to a difference in the general playing ability or education of each sample, but could also be a result of the limitations of translation during the interview process or the differing sample groups.

The only base theme to be present in the German map, but not in the English is that of ‘movement’ referring to the movement in the strings after a series of impacts. Since it is common for string movement to occur in any string bed, it may be that on the whole players deem it a too obvious and common occurrence to warrant comment. It might be expected that sufficient testing and extreme stimulation of this issue could disclose similar vocabulary in the English context.

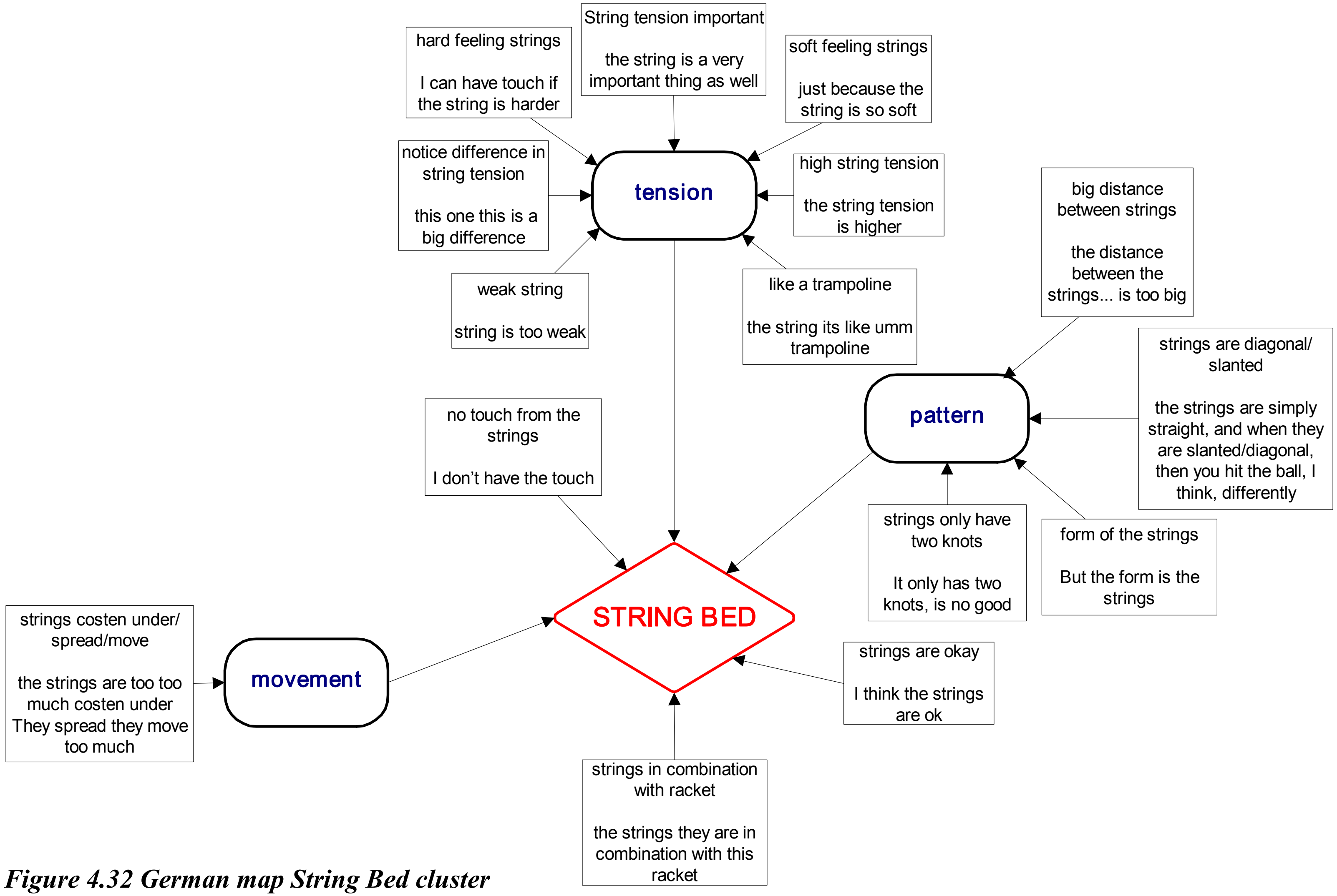


Figure 4.32 German map String Bed cluster

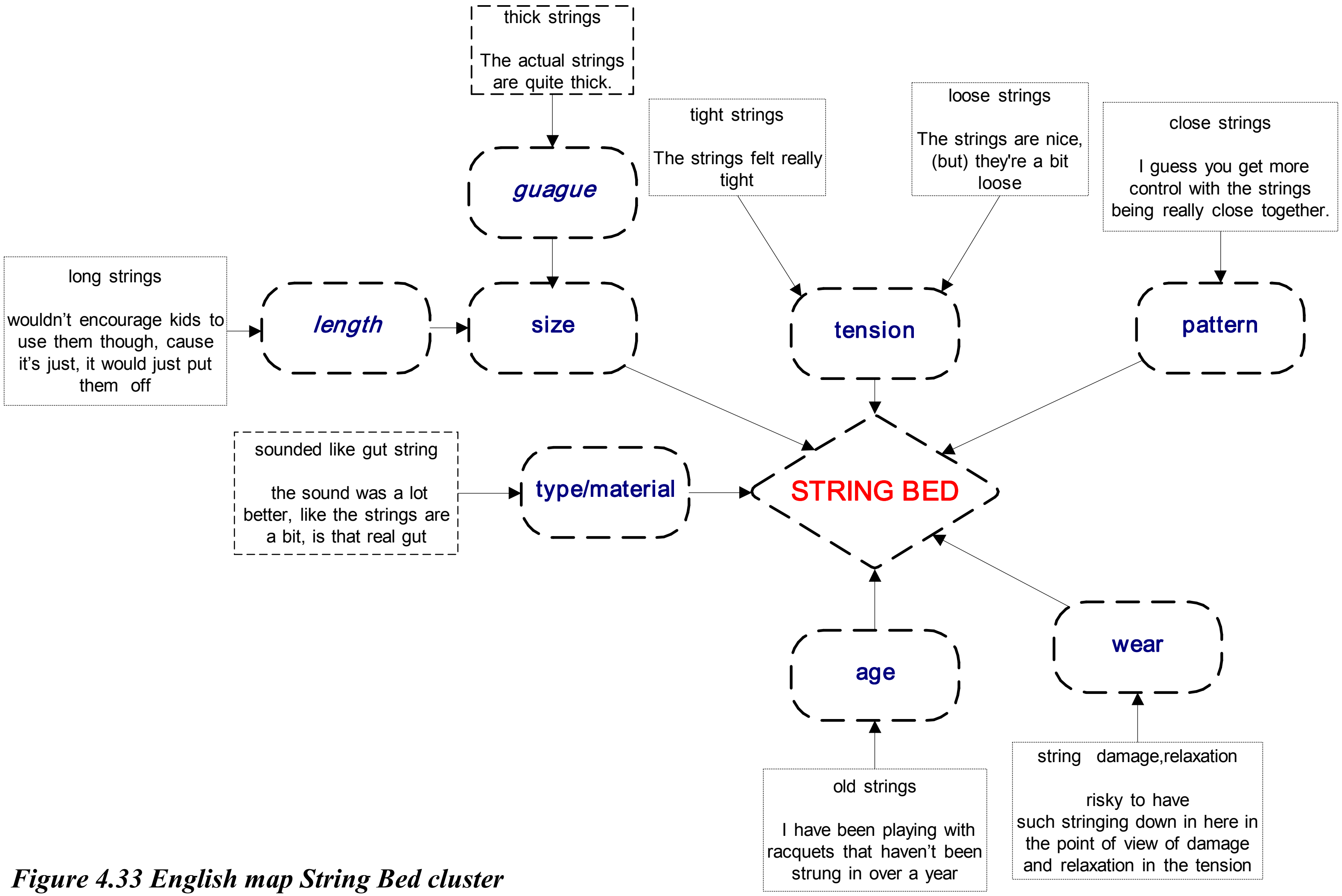


Figure 4.33 English map String Bed cluster

4.7 Summary

The postal questionnaire was developed to add new dimensions to the perception relationship model. It was felt that additions to the model such as relative importance and percentile use of vocabulary would significantly improve the use and application of the model. After several iterations questions were devised that would best provide this information, with relative importance rated out of 100% and vocabulary simply selected as "used" or "not used". The questions were written and constructed using vocabulary from the perception relationship model, so that players should be able to better understand the full meaning rather than potentially being confused by "technical jargon" which they may not be familiar with.

The distribution of the questionnaire posed a big challenge, a huge number of questions needed to be answered by a large sample, and returned and compiled into a table for analysis. The majority of the problems were overcome by creating a web based questionnaire and breaking it down into five smaller more manageable sections. Players across the country were contacted and asked to complete a section of the questionnaire. The web based program automatically compiled the data into tables which could be exported for analysis.

The compiled data was analysed and presented in a weighted lexicon which could be used to get more detailed information about entities from the feel map. The data was also presented in a more visual form embedded as part of the feel map. Relative importance was represented by a "shades of grey scale" with darker colours indicating higher importance. Percentile use of vocabulary was presented in the feel map as line thickness, with a higher percentile use entities having thicker lines and lower percentile use having thinner. These modifications aid readability and add greater depth of information than has previously been attempted with other sports equipment.

The resulting feel map and lexicon not only assists the user with a visualization of the relationships that exist between player perceptions and the associated tennis specific vocabulary, but also provides an amount of useful data that assists and diversifies its application. The map enables the user to create more educated player and test questionnaires, with a set of vocabulary less likely to be subject to misinterpretation.

The map can also be used as a research or design aid, with the relative importance ratings assisting with prioritization of issues and interdependency links indicating which additional factors should be considered or exploited for their influence on the characteristic area in question. The map and lexicon make up a perception relationship model that addresses half the hypothesis demonstrating that subjective testing can be enhanced. User perception of racket feel is now better understood using the full model.

CHAPTER FIVE

SMART RACKET DEVELOPMENT

5.1 Introduction

Subjective assessment of implement performance is of considerable but ultimately limited value to manufacturers without the ability to diagnose the true physical phenomena responsible for perceived performance so that these can be modified to achieve superior designs. In this chapter the research focus shifts to the question:

> "Can the modern tennis racket be instrumented in an entirely un-intrusive manner so as to make possible multiple simultaneous measurements of critical performance phenomena without inhibiting prolonged real play use or compromising/biasing a players perceptions of racket behavior?"

Clearly to begin to answer this question, the instrumentation requirement needs to be systematically defined and then design solutions formulated, prototyped and assessed in both controlled and realistic circumstances. Two alternative 'smart racket' systems were designed and tested, with a view to implementing the best performing system in fatigue and perception studies.

The first of these systems required the racket to be wired via 15 metre long cables to a computer. This system had some obvious drawbacks since the player had a restricted range, could easily become entangled in the wiring, and was likely to be distracted from their perceptions of the racket. The alternative versions of the systems resulted in the development of wireless data logging that became progressively smaller until the unit was small enough to fit in the grip of a tennis racket. During this refinement a number of problems were experienced with the signal quality. Laboratory testing in collaboration with the system developers overcame the majority of these issues to improve the application and reliability of the device.

5.2 Relevant methods and techniques

It was anticipated from the outset that this research would attempt to enable studies of both the effects of fatigue and players' perceptions since the published literature suggests these have yet to be adequately addressed. To fully investigate these issues previous research suggested racket acceleration, vibration, flex and grip force measures. For example, sufficient acceleration data might have enabled the calculation of angular acceleration of the racket to monitor how it changed as technique was altered as the result of fatigue or to relate the information to player feedback. Accelerometers have also been useful to investigate the vibration response of a racket.

Accelerometers are commonly used in racket research and a wide array of applications and mounting methods are demonstrated in the literature (Fairley 1985, Tomosue et al. 1992, Tomosue et al. 1994, Brody 1995, Cross 1997, Maeda and Okauchi 2002, Mohanty and Rixen 2002). In some cases the accelerometers have been used to investigate the shock or force experienced by the racket or arm (Cross 1998, Nab and Hennig 1998, Kawazoe 2000). Other studies have examined the transmission of vibration from racket to player (Maeda and Okauchi 2002). The differing applications have required alternative mounting locations, although broadly speaking, most have attached the accelerometers with wax or adhesive, rather than more rigid mechanical fixings and almost exclusively in one axis. Knudsen (1988) pilot tested the use of a tri-axial accelerometer but dispensed with it after it was deemed too heavy for the application, and thus failed to address the issue of multiple degrees of freedom data collection.

In a separate paper, Knudsen and Blackwell (1997) detail how a low mass accelerometer was used in conjunction with strain gauges and electrogoniometers to attempt to attain a more complete picture of the player/racket interaction. The electrogoniometers allowed player joint angles to be measured but were unable to measure the amount of wrist rotation. The strain gauges were mounted in such a way that representative measurements of torsion in the racket shaft were possible. Maeda and Okauchi (2002) also used strain gauges, pasted to the racket shaft, in conjunction with accelerometers to monitor racket vibration and its transmission to the arm. All of these examples of instrumentation were relatively bulky and required some amount of wiring that inherently inhibited the players to some degree.

Knudson also experimented with and published work concerning grip forces in both forehand and backhand tennis strokes (Knudson 1988, Knudsen and White 1989, Knudson 1991, Knudson 1997). In each case single point grip force sensors were used at no more than two points on the grip to examine changes in the mean grip force.

Eggeman and Noble (1985) developed and tested a transducer designed to be small enough to fit within a wooden baseball bat handle. The transducer only measured acceleration and still required some degree of wiring, but was discrete and was intended to be of minimal interference to the player. Anderson and Collins (2004) published work relating to the development of a real-time augmented feedback system for sports. As reported in Chapter 2 Anderson and Collins stipulate that a successful and useful augmented feedback system should address the following areas:

- The system needs to be flexible since it will need to be able to cope with a number of different data types, sample, bandwidths etc.
- The system must be very portable to enable the athlete to perform in their natural environment.
- The system and any wiring, sensors etc. must not interfere with the natural performance of the athlete.
- The data must be able to acquire, process and display the data required for the augmented feedback instantaneously.
- For a system to be marketed on a wide scale the system must also be a relatively low cost.

Not all these point are necessarily relevant for a purely research based application, but the prognosis is sensible and generally applicable and was considered when constructing a product design specification for the instrumentation required for this study.

5.3 Instrumented Racket Design Specification

5.3.1 Customer Requirement

Good design practice often begins with condsidertion of the customer requirement and subsequently the product design specification (PDS). In this instance the customer is considered to be Loughborough University Sports Technology Research Group and Head AG.

The customer requirement was for a tennis racket instrumentation system capable of fulfilling the following requirements:

- Once instrumented the racket should appear to be ‘normal’, suitable for extended, uninterrupted play.
- The system should be adaptable to fit a large range of different rackets
- The measurements should be repeatable and accurate for key performance phenomena appropriate to support the research
- The whole system needed to be created within the available budget and time scale

The PDS is separated into 2 sections. Issues critical to the success of the research were considered to be primary issues (Section 5.3.3, Table 5.1), those more commonly associated with a commercial product design specification or that were supplementary were considered to be secondary issues (Section 5.3.3, Table 5.2). Which measures of the rackets behavior in play are to be made is of fundamental importance to the smart racket design. Since there are a number of candidates and it is unlikely that all these can be simultaneously catered for their relative importance is discussed separately in the next section.

5.3.2 Potential Measures

The position, velocity and acceleration of the racket are all potentially useful measures that would aid in a comparative analysis. In theory they should all be capable of measuring the vibration present in the racket as well as any larger scale movement related measures. All these measures can provide physical data that is representative of the racket feedback perceived by players, indicated by the feel map to be an influential element of racket feel.

There are currently very few devices that are able to measure velocity directly and these are generally expensive, bulky and often only accurate over limited distances. Velocity is more commonly calculated indirectly either by integrating acceleration data or differentiating motion data with respect to time.

Motion analysis technology is able to take measures of body position and joint angles in 3 dimensions relatively accurately without encumbering the participant but often requires a number of cameras which can pose some problems. Vicon is a passive marker tracking system that is able to track movement to a relatively high degree of accuracy at high sampling rates, but requires a complex system of cameras that are difficult to transport and set up restricting its mobility and practicality. CODA is a more mobile active marker tracking system that is similarly reliable, although it can only be used indoors with appropriate lighting since it is sensitive to ambient infra-red light levels. The CODA cameras are also very expensive and although mobile are extremely ungainly and heavy, making them also difficult to transport. Both systems, whilst good for capturing a player's stroke, have inadequate resolution, accuracy and sampling rate to capture the vibration response.

Previous research has shown racket design characteristics affect strokes and timing (Mitchell et al. 2000b) and a player may perceive these necessary adaptations as is suggested by the feel map. Active marker systems require non-trivial instrumentation (i.e. infra-red flashes, timing electronics and power sources) that significantly add to racket inertia properties. Design solutions incorporating active marker backing electronics and devices to monitor other phenomena are likely to change its underlying frame characteristics to be a useful product assessment option.

Alternatively, passive marker solutions require nothing more than reflective markers of negligible weight to be added. Although, the burden in set up time for the hardware necessary to track these is an order of magnitude higher than for active marker systems they are the next likely preferred option for simultaneous multi-phenomena racket monitoring.

Strain gauges are capable of monitoring vibration from the racket frame. Strain gauges, however, are somewhat restricted in their mounting arrangement options, since they need to be placed on the frame itself, and thus generally have to be orientated in accordance with the design of the frame. This restricts the ability to examine vibration in any particular plane, and doesn't allow for the calculation of angular accelerations without extensive racket specific analysis.

Racket motion measured using accelerometers is a combination of rigid body movement, deformation due to impact/constraint, and excited vibration modes. Although classically dealt with separately in laboratory conditions, in play all three are inseparable. When selecting the number and location of acceleration measurements on the racket careful consideration as to which of these phenomena are relevant and relative priority is needed. Full modal response analysis of the racket would require the most extensive number and distribution. Whilst the results would arguably be close to laboratory equivalents with approximate gripping conditions, the true modal response could be measured under true gripping conditions.

A simple measure of acceleration represents the other end of the design spectrum. Arguably the ideal location to position this valuable, but limited resource would be within the grip aligned with the anticipated dominant acceleration direction. In this way elements of all three constituents (rigid body movement, deformation and vibration modes) are captured with respect to one degree of freedom. This latter solution has often been the case in previous research (Tomosue et al. 1994, Mohanty and Rixen 2002) but the accelerometer has not always been ideally situated (Fairley 1985, Brody 1995, Mohanty and Rixen 2002).

In research concerned with human perception/racket characteristic correlation and induced player fatigue the full scale model response of the racket is neither perceived by the player (except perhaps by the sound it makes) or imparted to their muscular-skeletal system except over the region of physical contact (i.e. the grip), and is thus excessive. Single degree of freedom measurements from, for example, a uni-axial accelerometer are by contrast inadequate since they fail to capture the other two translational acceleration components and all three angular degrees of freedom. Arguably acceleration in all 6 local degrees of freedom within the player's gripping region are responsible for force input into the hand and so tactile perception and fatigue, and should thus be the priority for measurement in this context.

Accelerometers are a well established technology commonly used in research. There is a wide and varied selection of transducers available on the current market that can accurately and reliably measure acceleration. There are a number of accelerometers that are small, robust and relatively inexpensive that would be well suited for mounting on a tennis racket, as required by the current line of research. Piezoresistive accelerometers are not particularly vulnerable to noise and are able to measure both low and high frequency vibration, they are also small and relatively inexpensive, but require a Wheatstone bridge for operation that requires hardwiring into the amplifier or data acquisition system, which can present a problem if not already included. Capacitance accelerometers are very similar in description only they are currently less common and require a variable capacitance half bridge circuit to interpret the signal, which also requires hard wiring. Peizoelectric accelerometers are more vulnerable to noise and will not measure any lower frequency vibration, but are small, inexpensive and are available in single and multiple axis form without the need for a Wheatstone or variable capacitance half bridge circuit. The vulnerability to noise can be reduced significantly by using noise protected cables and by protecting the instruments and wiring from too much adverse movement.

To be able to conduct an effective frequency analysis on the vibration data the sample rate needs to be at least 2.5 times the highest expected signal frequency of interest so as to avoid any aliasing effects. In this case it is expected the highest frequency of interest will be about 300 Hz, the approximate vibration frequency of the 2nd mode of a racket frame, so a minimum sample rate of 750 Hz will be required from the accelerometer data collection. To avoid overloading the sensors, the sensitivity of the system will generally be set so that for the majority of captures, the peak signal will lie between 25 and 75% of the full scale deflection. To limit the error to around ±0.1% for a signal amplitude 25% of the full scale value a 12 bit resolution is required, since this level results in a ±0.024% error of the full scale.

Grip interactions are arguably best described by the grip force exerted and experienced by the player. Both the normal and shear forces are useful measures to describe this interaction and thus provide physical data to correlate with the player perceptions of feedback, grip and potentially issues such as power and control. The size restrictions placed on the sensors that can be used for this application limit the range of available instruments to those which are thin enough to be un-detectably mounted between the grip tape and the racket frame. A number of instruments are available on the current market that would be able to measure grip measure, but many of these are too thick to be discretely applied under the grip tape, such as the RS Scan system or the Melexis pressure sensor, and others (e.g. Fuji Film) are not capable of dynamic grip force measurement. Dynamic pressure sensitive films, however, are ideal for this type of application but are limited in as far as they are unable, at present, to accurately and reliably measure shear force. Despite the apparent usefulness of shear force data, current technology, within the budget and time restraints of the research, is not capable of making the required measurements. Irrespective of the lack of shear force data, normal force data is undoubtedly useful and the TekScan Flexiforce dynamic force film sensing technology is available and capable of providing the data required.

TekScan is a piezoresistive ink technology with typically 96 pressure measuring cells on a 86.4 x 343.4 mm sensor. Resistance between electrode pairs aligned either side of the ink layer is burst sampled via metallic tracks attached to a protective insulating outer laminate. The tracks are contrived so as to minimise the number of connections required at the standardised interface necessary to assess resistance across all intended electrode pairs.

The bulk of the literature in this area utilises one or two pressure points on the tennis racket grip to measure the normal dynamic force exerted by the player throughout the stroke. Although there is justification for these points alone to be monitored, it is generally the limitations of the available equipment that has been the overriding factor in the decision. With the introduction of the TekScan dynamic force sensitive films to the commercial market it has become possible to achieve full grip coverage, which should help to provide the data necessary to fully investigate the areas that have been previously unobserved. The TekScan system requires relatively large and ungainly cuffs to be mounted in the immediate vicinity of the film sensors, which is not desirable when investigating elements of player perception that would be severely compromised by such a bulky addition to the player's arm. Further to this the system has a limited sample rate and is only reliable when observing a relative change in pressure, the absolute measures are far less accurate. The sample rate allowed by this system of up to 220 Hz means, given that impact generally occurs over 4 or 5 ms, only a 1 or 2 data points are possible to be captured in one peak to peak cycle. This sample rate is clearly not high enough to accurately examine peak grip forces, but is sufficient to provide a reasonable assessment of more general grip activity.

The FlexiForce system does not require the same bulky cuffs and sample rate is only limited by the data acquisition system used. Since it is a single cell system, it can be calibrated more easily and accurately. This means FlexiForce can provide more reliable absolute measures of pressure. However, the single cell nature of the system means it is difficult to obtain large area grip coverage. It is conceivable that the TekScan system could be used to investigate the grip as a whole and highlight areas of particular interest and the FlexiForce system subsequently used to focus on these areas in greater detail.

In spite of its low average relative importance rating, the 'sound' cluster in the feel map was linked with a number of interdependencies indicating that it is an influential element of overall racket perception. On this basis sound data would clearly be of some benefit to the research. Numerous forms of microphone and sound recording methods exist and many are appropriate for capturing sound accurately in a static situation. Roberts (2002) measured the sound from golf impacts using 2 alternative methods. It was deemed important due to the nature of the propagation of sound to record in the vicinity of the human ear, so one of Robert's methods mounted two microphones on a hat one above each ear. As an alternative method, Roberts mounted the microphones on the ground a distance away from the impact equal to the distance from the impact to the ear. This technique was judged to be more appropriate given its less intrusive nature. In the context of an instrumented racket system a microphone could be mounted on the racket itself. One draw back to this solution is the fact that the distance from the racket head and thus impact location to the ear can change from shot to shot. This means that the sound heard by the player will not be the same as that detected by the microphone, and cannot be normalised given the continuous variation in distance. For a similar technique to be implemented in tennis, the player would have to hit balls from a static feed, restricting their movement, or wear some form of headwear that could in itself potentially interfere with player perception. Within the context of a 'smart' racket, the sound detection equipment would have to be mounted on the racket frame, which, in addition to the problems associated with the quality of the data captured so far from the player's ear, would be difficult to mount discretely and would leave little room for any further instrumentation.

Although vibration data from a racket should give some indication as to when an off-centre shot was struck the exact location of impact would be unknown. This information is useful to examine the perceived sweet spot location and size to correlate with vibration and power data and to help explain unusual or unexpected results. Some methods have been devised to measure the location of ball impact on the string bed, but these have generally involved complicated, encumbering or restrictive instrumentation or not been particularly accurate (NaB et al. 1998, Miyashita et al. 1992). Other feasible methods of determining impact location include an optical system and a string force system. An optical system would require a series of light gates forming a grid on the string bed. These gates would be fairly conspicuous unless they could be machined into the frame and would require cabling and logging equipment that would not leave much room for any further instrumentation.* A string force system might utilise pressure sensors between the string grommets with higher measures evident adjacent to where the ball impact occurred. This system would be less conspicuous, but would still require cabling and logging equipment that would limit opportunities for further instrumentation. Essentially the measure of impact location, although desirable, is difficult to attain and non essential in as far as other instruments are capable of measuring the resulting effects.

* (The author is aware of such a system in the possession of the ITF, but has been unable to source a suitable published reference)

Ball speed, spin and bounce location are also generally considered important measures of racket performance. Although theoretically appealing, smart racket technologies able to measure these three phenomena from a location within the racket frame are difficult to conceive of. Measurement solutions external to the racket frame are far less difficult to achieve offering the benefits of both expediency and previous published use.

The landing location of the ball is indicative of accuracy and thus control, an issue indicated by the feel map as having a high relative importance and a large influence on overall racket perception suggested by the number of interdependency links. There are a number of methods reported in the literature for assessing landing location, (Avery et al. 1979, McCarthy 1997, Thout et al. 1998, Stanbridge 2003 and Bowyer 2003) which were all considered and adapted to create a new method of accuracy data collection involving a marked out grid and associated scoring system described in more detail in Chapter 6 (Section 6.5.2).

Alongside control, ‘power’ as an aspect of feel had a more highly rated average relative importance and high number of interdependency links indicating that it was an important element of racket performance. A good indicator of a racket’s power is the resultant ball speed. Various methods of measuring ball speed are reported in the literature (Avery 1979 Stanbridge 2003, Brody 1993), but for the purposes of this research, and in the interest of comparable results the use of a Doppler shift SpeedCheck radar as used by Bowyer (2003) was deemed to be the most appropriate method.

Ultimately the onboard instrumentation was prioritised, space permitting, in the following order:

i. 6 degrees of freedom racket grip acceleration
ii. 2 point grip force
iii. Full Grip force
iv. Full 3D racket motion tracking

5.3.3 Primary and Secondary Specification Issues

The following tables present the proposed smart racket design specification

Table 5.1 Primary design specification elements

Performance	Measure types	• Acceleration – 6 degrees of freedom achievable with 6 appropriately mounted accelerometers • Grip pressure (e.g. TekScan or FlexiForce pressure sensors discretely mounted beneath the grip tape) • Racket motion – lower priority, passive marker system acceptable
	Resolution	• Below 12 bit resolution will make for an unacceptable error range greater than 0.1% • 12 bit resolution required for an acceptable ±0.1% error range at 25% of the full scale • 16 bit resolution for an ideal ±0.06% error range at 25% of the full scale
	Sampling rates	Angular and linear accelerations: • A sample rate of at less than 750 Hz, will be unacceptable since below this level the frequency is insufficient to conduct frequency analysis on the vibration frequencies expected from impact • A sample rate of around 1000 - 2000 Hz would be suitable since frequency analysis will be possible and samples per peak will be sufficient for peak to peak values to be assessed to some degree of accuracy • A sample rate upwards of 3000 Hz would be ideal to achieve more accurate and consistent peak to peak measures

Performance (continued)	Sampling rates (continued)	Grip force pressures: • A sample rate of less than 50Hz would be unacceptable since this level is required to get a reasonable overview of grip activity • A sample rate of 250 Hz or more would be acceptable to examine in more detail the changes and peak forces that occur during impact. • Ideally the sample rate would be more than 2000 Hz so as to be able to examine the finer details of grip response to vibration
	Period of capture	• The ‘smart’ racket system must be able to capture 10 impacts worth of data; any less would make testing impractical and would be unacceptable • A system capable of capturing for a period of 30 minutes with a total number of impacts numbering between 300 and 500 would be acceptable to allow for extended play tests • Ideally the total capture time would exceed 3 hours for optimal flexibility, multiple tests and to allow for margin of error considerations.
	Collection and analysis interface	• The system must be able to transfer data automatically to a computer within 30 minutes, so as to not leave an unreasonable time between tests. • The system should, as a minimum requirement, be able to transfer data using standard communications technology (e.g. USB, IEEE 1394, Bluetooth etc.) to a computer. • Communications software should generate data files in aMicrosoft Excel compatible format. • Ideally the system will be capable of wireless real time data transfer direct to a computer to allow instantaneous monitoring of the data.

Size, Weight and Ergonomics	Extremes of the market range	• Additions of smart instrumentation to any new racket design should have minimal effect on the following and other racket characteristics so as to allow unbiased assessment of its performance.
		• When this is not possible greater affects may be tolerated where the resulting smart racket allows performance phenomena to be studied within the market range.
		• Racket characteristics and the market range:
		    ○ Mass: 220 - 400 g
		    ○ Length: 67 - 73 cm
		    ○ Width: 22 - 29 cm
		    ○ MOI: 280 - 430 $kgcm^2$

	Weight	• An increase in weight of more than 100 g additional racket weight would impinge on the minimum required test range of 20% of the maximum market weight so would be unacceptable • An increase of between 30-100 g would be acceptable since this would put the racket well inside the market range and allow for a reasonable test range • Ideally the racket weight increase would be less than 30 g to attempt to minimize the change in the racket keep it near the middle of the market range
	Length	• An increase in length of more than 6 cm would increase it outside the acceptable extremes of the market range. • An increase of less than 3 cm be acceptable and would keep the racket within the market range

Size, Weight and Ergonomics (continued)	Length (continued)	• Ideally there would be no increase in the racket length to minimize the change in feel and performance of the racket
	Moment of inertia	• An increase in moment of inertia of more than 105 kg.cm^2 would be unacceptable since it would not allow for a 10% test range that was still within the extremes of the market range. • An increase of between 25 - 105 kg.cm^2 would not change the racket too dramatically and allow for a large test range so would be acceptable • A change of less than 25 kg.cm^2 would be ideal to minimize the change in the racket's feel and performance
	Grip	If the grip size is increased outside the market average (grip size 3.5-4.5) the system will be deemed unacceptable, thus any data capture hardware will have to be mounted within the following dimensions: • Width: 23 mm • Height: 14 mm • Length: 185 mm
Environment	Use and context	Courts used for testing may be situated indoors or outdoors. The instrumentation system should be able to comfortably withstand the demands of these environments
	Temperature range	Indoors – generally within ambient temperature ranges i.e. 16 - 30^{o}C Outdoors – generally within climatic average ranges i.e. -5 – 35^{o}C
	Humidity	Indoors – generally within ambient temperature ranges i.e. 20 – 60% Outdoors – generally within climatic average ranges i.e. ~0 – 100%

Environment (continued)	Salt water	Salt water, in the form of sweat may be present at the grip/hand interface. The design should make adequate provision to protect sensitive electronics from exposure.
	Surface	Testing may be conducted on clay, grass, asphalt or hard court surfaces. With each surface type are associated connotations of dirt and grit with may come into direct contact with the system
Durability/ Life in Service	Direct impacts	Any external part of the system may be exposed to direct ball impacts travelling at up to 250 kmph
	Repeated string impacts	The system will regularly experience the effects of string bed impacts, which can results in vibration frequencies up to 1500 Hz and peak acceleration up to 500 g
	Ground strike	The racket is also likely to be exposed to ground strikes with could generate amplitudes > 1000g
	Continuous use	• A continuous use time of less than 45 minutes will be unacceptable since this is the minimum amount of time required to conduct any useful testing • A continuous use time of between 2 and 4 hours would be acceptable since this would allow for multiple tests to be conducted without the need for a time consuming recharge • Ideally the continuous use would exceed 4 hours at a time to allow testing to continue for a day at a time without the need for a recharge
Installation, Changeover and Maintenance	Adaptability	• A system only compatible with a single racket will not be able to be used to test any variety of rackets or keep pace with the rapidly progressing market so will be unacceptable • A system capable of fitting any of the Head racket range would be acceptable since this could be utilized for ‘in house’ testing and comparison between racket designs. • Ideally the system will be able to be fitted to any racket regardless of manufacturer or type for maximum application flexibility

Installation, Changeover and Maintenance (continued)	Maintenance frequency	System maintenance of the system may include replacement or readjustment of sensors, wires and power sources e.g. batteries. • A system that requires any form of maintenance before the completion of one racket change, will be unacceptable since this could leave a data set incomplete • Daily maintenance would be acceptable since this would allow for a full days uninterrupted testing • Ideally the system would be able to be taken away for a week or more at a time without the need for any maintenance
	Maintenance Duration	• A maintenance time of more than 5 minutes would not be very suitable since this could interrupt the flow of testing, and really encroach on the available test time. • An acceptable maintenance time would be between 1 and 5 minutes since this would be able to be conducted quickly without significantly affecting the test schedule • Ideally maintenance would be able to be completed in less than 1 minute which would could be conducted at anytime without with out any real interruption to testing
	Installation/ Removal Time	• Should the system need to be removed and reinstalled during a test for any reason 5 minutes or more would severely encroach on the test so would not be acceptable • An installation or removal time of between 1 and 5 minutes would be acceptable since this would easily be achieved without having to terminate testing due to lost time. • A time of less than 1 minute would be ideal since this would allow maximum flexibility and minimum impact on test timing

Aesthetics	• Ideally there would be no detectable change to the racket aesthetics so as to eliminate any possibility of visual distraction or interference with perceptions
Manufacturing Process and Materials	• Head racket manufacture factory and general and advanced workshop facilities at Loughborough University were available • Custom data capture electronics were to be supplied by research partners (i.e. Head and BTI) • Limited sensor innovation and assembly from ‘off shelf’ commercially proven technology was recommended to reduce development time scales and costs
Calibration	• A system that is unreasonably difficult to calibrate and requires frequent recalibration would be unacceptable • A system that is simple to calibrate and need only be recalibrated at the end of each study would be acceptable • Ideally the system would be able to be calibrated in situ and rarely need recalibration
Production Quantity	• One set of instrumentation to be easily added to any racket would be sufficient if it were robust enough and easily transferred from racket to racket • Ideally multiple systems would be produced to serve as back up to the one in use or to equip many rackets simultaneously

Table 5.2 lists the identified secondary design specification elements

Durability	Product lifespan	• If the system cannot last long enough to complete an entire study, it would be unacceptable • A system with a lifespan that will last for the duration of the PhD research will be acceptable • Ideally the system will last for as long as it is required or is rendered redundant by replacement technology
	Shelf Life	• A system that is unable to be stored for any length of time would be unacceptable • A shelf life of around 1 year allowing the system to be stored without degradation of performance between tests would be acceptable • Ideally the system would have an unlimited shelf life, with the system ready for use at any time
Marketing/ Competition		• The system is design for in house use and not for commercial resale so consideration of patents is not important

An initial review of the specification revealed the possibility of two types of system: one where the instrumentation is permanently embedded in a racket and one where the instrumentation can be shared by a number of rackets. Although the first approach arguably results in the least intrusive design the cost in terms of sensors and data acquisition hardware was prohibitive. Thus the preferred design solutions adopted ‘swappable’ system designs.

Subsequent design solutions could also be divided into two approaches: one based on readily available wired instrumentation solution, the other based on wireless data acquisition hardware. The first provided an opportunity to make an initial foray into player testing within short time scales in support of already ongoing research (Bowyer, 2003). The second solution type posed problems in that none of the commercially available portable data acquisition systems had sufficient capacity or were small enough to embed within the racket. However, Head Tennis AG had entered into a relationship with BTI (a small Austrian innovations company) to provide an appropriate data acquisition device* based on their expertise in miniature battery cell technology.

The following sections report the development of the two design solutions pursued under these ‘wired’ and ‘wireless’ approaches

5.4 Wired Design Solution

5.4.1 Sensor Selection

At the time of the research there were no commercial available 6 degrees of freedom accelerometers. However, a miniature 3 degrees of freedom linear tri-axial accelerometer (Endevco Model 23 tri-axial piezoelectric accelerometer) was available and of suitable size and weight to measure translations at the grip centre. The inherent size of the grip meant that space was very restricted, particularly with the necessity of three axes considered. The Model 23 tri-axial accelerometer was billed as “the world’s smallest tri-axial accelerometer”. Although relatively expensive the accelerometer, unlike that trialled by Knudsen (1988), was light weight, fitted comfortably into the grip, could operate in the three axes required and the budget was

*(to the authors specification where possible)

sufficient to make it affordable. Due to the high cost of the equipment a 'swappable' mount was required so that a single accelerometer could be easily transferred between rackets rather than permanently mounting several sensors.

A second 3 degrees of freedom tri-axial accelerometer to gain 2 angular acceleration measures was too expensive given the limitations of the budget. Angular accelerometers commercially available at the time of the research were too large and heavy to be mounted on the frame without substantial effects on the perception and performance of the racket. An alternative solution required 3 uni-axial 1 degree of freedom accelerometers offset from the grip mounted tri-axial accelerometer. A method of mounting the uni-axial accelerometers at the required location had to be developed for this solution.

A piezoelectric Bruel and Kjaer model 4375V uni-axial accelerometer was identified that was readily available, and accurate and small enough to be integrated into a racket instrumentation system. This particular model accelerometer also shared the same interface as the Endevco Model 23 tri-axial piezoelectric accelerometer. An alternative Endevco 7263B piezoresistive accelerometer was also considered. The product specifications suggested that the accelerometer would also be suitable, and would be less vulnerable to noise due to its resistive rather charge based measure. Unfortunately they were not available within the initial testing timescales.

Although previous work had been concerned with single or dual location grip pressure measurement (e.g. hypothenar and thenar eminences) it was decided that a solution to monitor the whole grip region was desirable to more fully study the phenomena. It was anticipated that this might merely prove the wisdom of previous dual sensor measurement locations, but with changes in grips and strokes this was not certain.

TekScan was a relatively new system on the market that allowed large area coverage with dynamic pressure measurement. The pressure sensor selected had cells arranged in a 6x16 grid on the 86.4 x 343.4 mm sensor that could be cut to shape to best suit the sensors application. The width of the cells was approximately equal to the width of each of the flats on a tennis grip allowing 6 of the 8 grip flats to be covered with a single sensor. This system was deemed to be the most appropriate for the racket instrumentation system since the comprehensive dynamic tennis grip response was as yet un-documented in the research literature.

5.4.2 Sensor Mounts

With the appropriate equipment selected, the task of mounting the instruments had to be tackled. The ideal solution would:

- be light weight so as to have as little effect as possible on the racket characteristics
- be discrete so as to have minimal visual impact on the player
- provide a solid base in a good position for the equipment to capture the best possible data
- be able to be transferred from one racket to another quickly and easily
- offer a degree of protection to the equipment

Tri-axial Accelerometer Mount

A section of the inside of the racket handle was machined out to allow a polypropylene plastic bracket to be inserted inside, directly under the player's hand. The bracket was shaped to fit a removable polypropylene plastic mounting, into which the tri-axial accelerometer could be fitted securely minimising any adverse movement (figure 5.1). These brackets provided the instrumentation with:

- protection sufficient to withstand a tennis ball impact
- optimal locations for signal capture
- added weight to the racket that was small enough to still be considered within the market range
- a method of removing the instruments quickly and easily

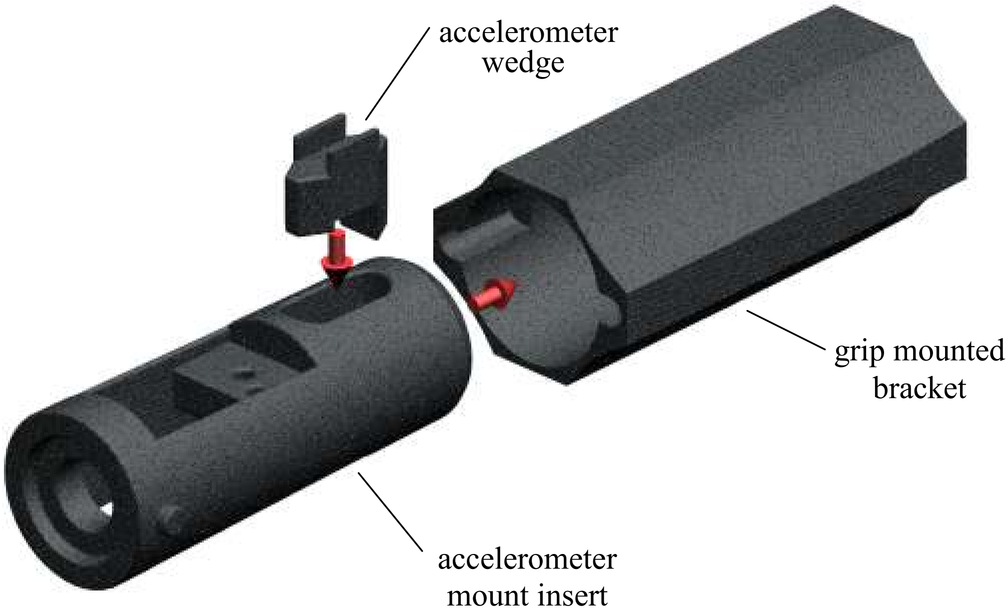


Figure 5.1 tri-axial accelerometer mount from racket butt (Bowyer 2003)

Uni-axial Accelerometer Mount

For the additional 3 uni-axial accelerometers the use of mounting wax, or other adhesive was considered, with the equipment mounted directly onto the racket frame (as commonly reported in the literature). This method would be easy to implement, did not require any additional mounts to be constructed and thus had minimal impact on the characteristics of the racket. Provided the accelerometers were mounted securely, with a resin or strong glue for example, then the data would not be particularly vulnerable to additional noise from movement, or signal dampening from absorption from the mount.

However, the advantages of the ease of mounting were outweighed by the restricted number of places on the frame that are suitable for mounting equipment where the instrumentation would be able to capture a good signal, be protected and have a flat mounting surface in the appropriate orientation. In addition, should the adhesive utilised be strong enough to safely secure the equipment, it would most likely be difficult to remove the instruments, making racket changes more problematic. This problem was compounded if a dissimilar racket frame was used when the equipment was swapped since the possible mounting locations would most probably be different.

It was apparent that new mounts would have to be developed to best meet the specifications discussed. The first iteration of the new mounting method saw the three uni-axial accelerometers being secured to the throat of the racket on an aluminium bracket machined to fit the frame in such a way that relative movement of the bracket in relation to the racket was minimal (figure 5.2).

Figure 5.2 wired system uni-axial accelerometer throat bracket mount

Grip Pressure Mounting

To take measures of grip pressure a TekScan 96 cell sensor was partially divided into six strips and secured to the racket with double sided tape. Each strip was attached to one of eight flats on the tennis racket grip, until six adjacent flats were covered. Grip tape was then wrapped over the grip, to protect the sensor and to replicate the tactile and traction qualities of the non-instrumented rackets (figure 5.3).

Since only six of the eight grip facets could be covered with the Tekscan sensor, the decision as to which two flats would be left uncovered had to be addressed. Of the eight flats (figure 5.4), the top flats were expected to experience the highest forces during the down stroke of a backhand slice technique, the front and back flats were expected to experience forces whilst accelerating and decelerating the rackets horizontal planar velocity. The ‘bottom’ and ‘bottom, front corner’ flats would be in contact with the middle phalanges and thus likely to experience lower forces and of less relative interest than the others. The ‘bottom, rear corner’ flat was covered in preference to the ‘bottom front corner’ flat due to the fact that in a standard backhand grip this was

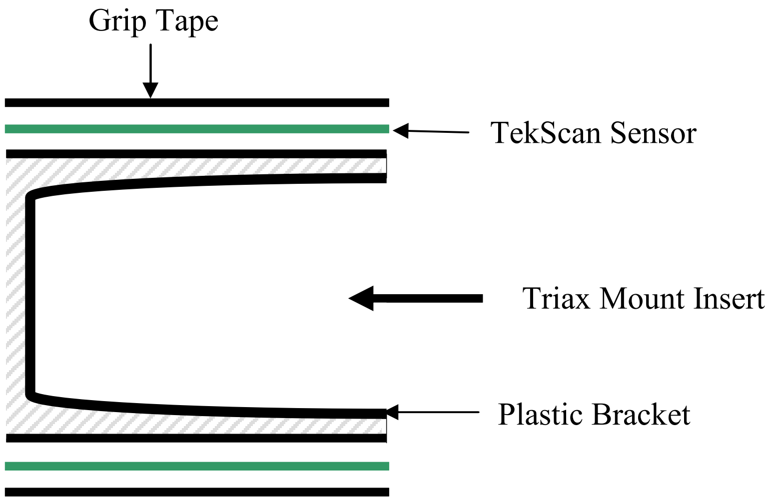


Figure 5.3 Instrumented racket grip cross section

where the finger tips were likely to lie. This might highlight some tactile control differences in different player groups, e.g. do elite players, when compared to recreational players, make more fine adjustments to the racket with the fingertips to aid control and consistency.

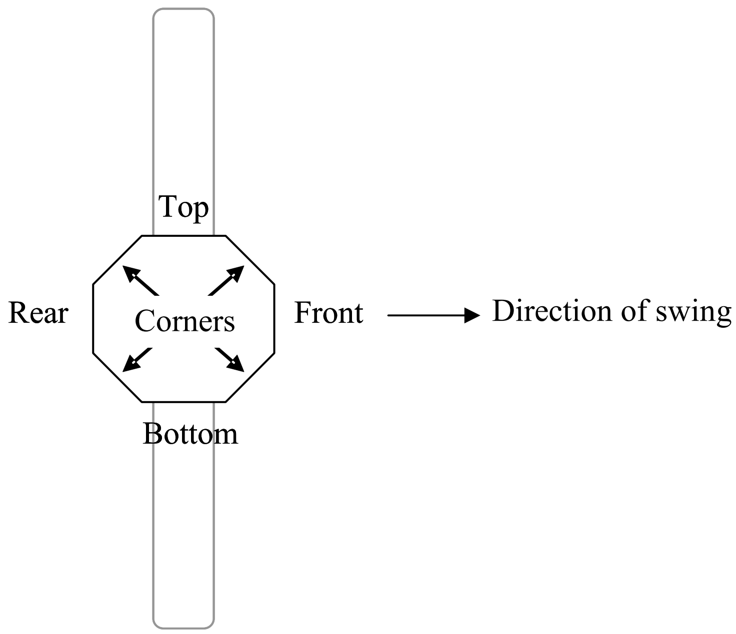


Figure 5.4 Labelling of grip flats

5.4.3 Data Capture System Setup

Each of the piezoelectric accelerometers has a noise protected connector leading of it. To allow enough length of cable for the player to be allowed up to 3 m of freedom the connectors needed 10 m extension cables be run along the racket and player's arm and off the body and to the data acquisition equipment.

The effect of using different wires was researched to help understand how this noise might be reduced. If the coaxial layers in the wire are separated, as is possible through movement or 'kinking' of the wires, then a capacitance charge can be stored, which can then upset the true signal sent to the charge amplifier. This noise is minimised by using noise shielded wires, which incorporate a conducting layer in the cable to discharge any the undesired charge stored as a result of the separation of the layers.

Through experimentation it was discovered that the wires were most sensitive to noise where there was movement at the junction between wire and connector. Care was taken to ensure the coaxial wires were secured such that movements of the wires at the junctions to the accelerometer and charge amplifier were minimised. The junction between the wire and the accelerometers occurred on the racket itself where the wires were, in the case of the uni-axial accelerometers, secured to the racket frame. In the case of the tri-axial accelerometer a rubber wire clamp was devised which held the wires firm once the mount was secured in place.

The signal direct from the accelerometers was optimised through Bruel and Kjaer four channel charge amplifiers before it was fed via a Hewlett Packard eight channel BNC connector and then on to a Hewlett Packard analyser used to interpret and condition the signal. An IEEE 1394 'Firewire' connection allowed high speed data transfer to the computer. The software interface, Signal Calc 620, was configured with the amplification settings for each channel of the charge amplifiers and used to filter and manipulate the data.

Initial testing displayed a persistent offset in the signal even when a zero reading was taken from the accelerometers. The signal was diagnosed as a DC offset generated by the Hewlett Packard analyser. By AC coupling the signal interpreted by the software the offset was filtered out. AC coupling, generally achieved in electronics by running the signal through some form of capacitor, filters out low frequency DC noise, and allows the higher frequency AC (alternating current) signal to pass. The majority of readings prior to impact involved with the swinging of the racket would be low frequency (i.e. effectively DC). Since the piezoelectric accelerometers available were not very sensitive to low frequency fluctuations AC coupling did not seriously compromise the data. The source of the DC offset was attributable to the HP analyser based on advice from the tri-axial accelerometer manufacturers.

The Tekscan sensor connector interfaced with a burst sampling data buffer cuff that fed the signal via 10 m long cables to a computer. The Tekscan software interface allowed the signal to be interpreted and stored.

To help keep the system neat, reducing the chances of kinked wires, and snags on the player, the wiring was led off the racket along the TekScan connection ribbon loop which was run in such a way that, when the racket was gripped in a backhand, it would run over the knuckles of the player so, in as far as possible, interference with a stroke was minimised (figure 5.5). Running the wiring along the Tekscan connection had the added affect of reinforcing the wires reducing the movement and, therefore, any potential noise produced by them (figure 5.6). It was decided that running the wires in this way was better than having them run under the grip tape along the unused flats, since this would affect the pressure distribution of the player's grip.

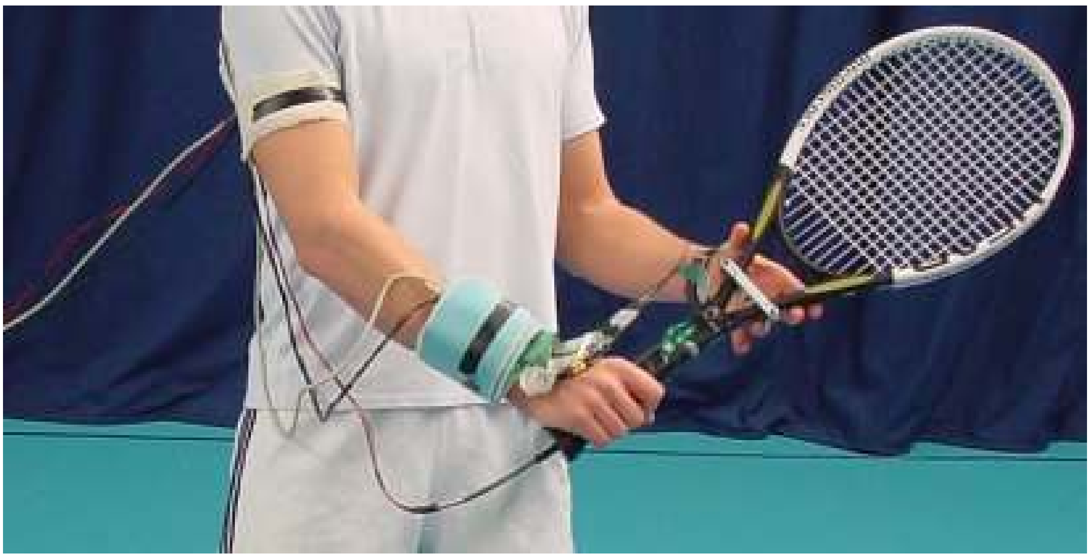


Figure 5.5 Tekscan connector running over the player's knuckles and wrist

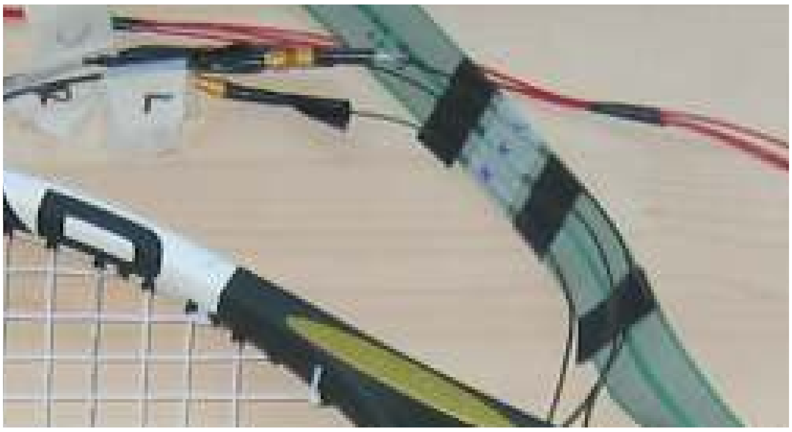


Figure 5.6 Uni-axial accelerometer wires coupled with Tekscan connector

The whole system was synchronised using a TekScan trigger box configured to trigger both TekScan and Signal Calc. The trigger box was linked to the eight channel connector via its BNC port, and to the TekScan computer via its serial port. Figure 5.7 shows a schematic of the system setup.

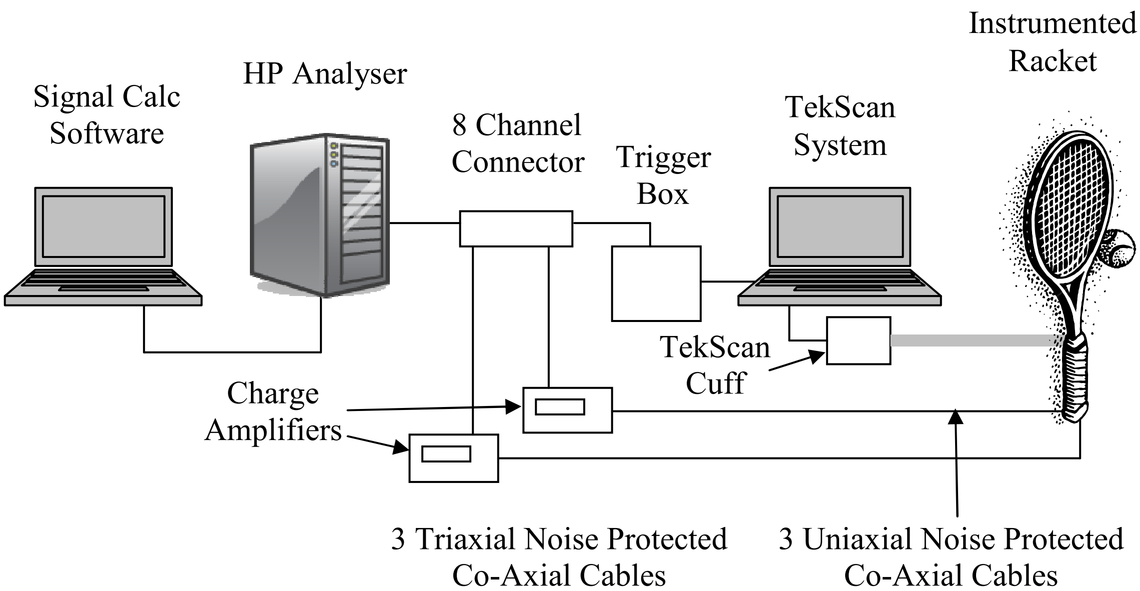


Figure 5.7 Schematic of experimental setup

The trigger system devised to enable the synchronisation of all the signals captured from the various sensors was adapted to account for the coupled signal. The button on the TekScan trigger box had the effect of triggering the TekScan equipment to start capturing at the same time as sending a large DC signal to the 8 channel connector. The Signal Calc software was set so that, unlike the other 6 channels connected to the accelerometers, the channel receiving this DC signal was AC coupled so as not to filter it out.

5.4.4 Initial Application

Fatigue Testing

The wired data acquisition system was used with some success in localised muscular fatigue testing for research conducted in collaboration with Bowyer (2003). The test involved attempting to fatigue the active muscles involved in playing ground strokes then asking the player to hit slice backhands with the instrumented racket. The player was instructed to hit shots continuously for 3 minutes following a pattern of one forehand to two backhands repeatedly followed by a recovery period of 1 minute. With the relatively quick ball feed rate the player would experience some degree of muscular fatigue over 3 sets before exchanging that racket with the instrumented racket. The player would then hit 15 back hand sliced shots at a slower rate whilst data was captured from each impact.

Although the results raised concerns over the sample rate and accuracy of TekScan, on the whole the system was successful in capturing good quality data and allowed the player to hit relatively natural shots. However, due to the extensive wiring of the racket, a separate non-instrumented racket had to be used during the fatigue process, which involved a lot of body twisting to hit successive forehand and backhand shots, and would have otherwise inevitably resulted in the player become entangled with wires. Changing racket resulted in a degree of recovery in the players' musculature, thus limiting the level of fatigue that could be achieved for the measured set. The wired system not only affected this set of testing but severely limited its application in, for example, perception studies or full body fatigue experimentation.

5.4.5 Secondary Application

Un-fatigued Testing

The wired instrumented racket design was used in a second application to simultaneously capture racket performance with racket and player motion, muscle activation data and ball velocity. Testing took place in the Loughborough University gymnastics centre since it is equipped with a Vicon motion tracking system. A pair of Genlocked high speed video cameras were used alongside the instrumented racket to provide dynamic motion data on the test participant and ball.

The length of a tennis court was marked out with white masking tape down the vault runway and a net erected to the correct height in the middle. A Bola ball launcher was positioned opposite the participant at the far end of the runway, and set to simulate an incoming ball as might be played in a match. This feed was based on the player's assessment of ball speed and trajectory.

Eight rackets were used for the test: four LM Prestige and four LM 8 rackets. One of each type of racket was strung to a tension equivalent to that in the participant's racket and marked up with Vicon markers, but were otherwise un-instrumented. This allowed motion data to be collected for some entirely un-inhibited shots, for comparison with subsequent shots with a more heavily instrumented rackets (Glynn 2007)

For the most fully instrumented trials Tekscan sensors were attached to the grip, as with the previous test, of one of each racket type. Unlike the previous test two sensors were used on each racket to give full grip coverage requiring 2 interface cuffs. The sensors were mounted on plastic strips to cover the uneven and soft PU foam surface, not present on the rackets used by Bowyer (2003), which were secured to the grip with double-sided tape. These rackets were also strung to a tension similar to that in the participant's racket. EMG data was taken along with the Tekscan grip data. With the use of two Tekscan cuffs and a multitude of wires for the EMG system the player's movement ease was compromised.

To capture data with a reduced instrumentation burden the remaining four rackets were intended to be instrumented with throat and grip mounted accelerometers, flexi-force pressure sensors that did not require any bulky interface cuffs coupled with EMG, Vicom and high speed video data. The original triaxial accelerometer mount fitted into the grip of previous test rackets would not fit inside the Liquid metal racket range, so uniaxial accelerometers were to be mounted into the surface of the PU foam grips. The low profile accelerometers required to mount on the grip were not available from the supplier so alternatives were identified. Delivery of these accelerometers was delayed so that they were not available for testing and had to be omitted.

The available uniaxial accelerometers were mounted on the throat of the racket, as in the previous tests, on an aluminium bracket clamped to the frame. Two brackets had to be made to fit each of the different racket frame styles. Six accelerometers were used so that they could be left attached to the brackets to save time between tests.

The Flexiforce sensors were mounted on the PU foam grips by sticking low profile centimetre squared pieces of plastic, secured with double sided adhesive tape to the surface of the grip. These gave a smooth and rigid surface to measure pressure against. The sensors could then be attached with more tape to the plastic squares. Grip tape was wrapped around the rackets over all the Flexiforce sensors. The position of the sensors was determined from a meeting with the participant to discuss which areas of the racket they felt they experienced the highest pressures from. Although two points were required for both the topspin and slice grips, one of the points happened to coincide for each grip so only three sensors were required for each racket.

Of the four rackets, in an attempt to give similar string bed stiffness, one LM Prestige and one LM8 were strung up at 70 pounds and 75 pounds of tension respectively. The other two rackets were planned to be strung at 57 pounds, but due to time restrictions they were left unstrung and the two rackets used earlier in the test for the “free hitting” were instrumented “on site”.

All equipment and instrumentation was synchronised with the use of a trigger system. The trigger button was a wireless device that sent a signal to the Vicon system and a trigger box remotely. The Vicon system received a signal that was recorded along with the motion data. The receiving trigger box for the other systems sent a falling square wave signal to the rest of the equipment as shown in figure 5.8.

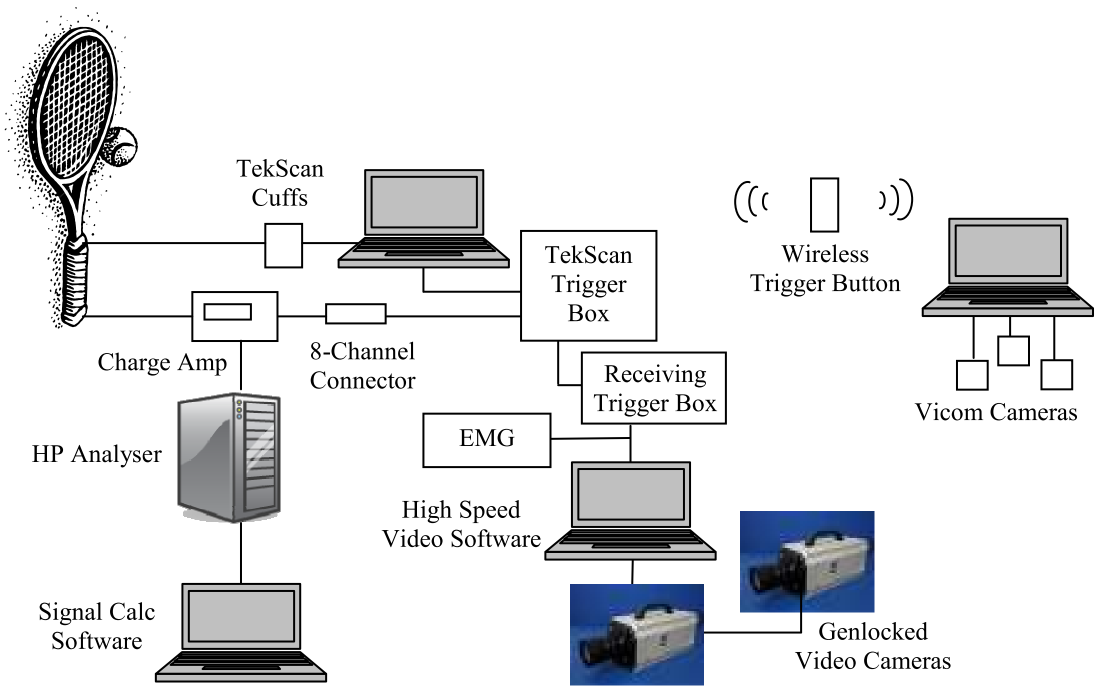


Figure 5.8 Experimental system diagram

A wireless remote trigger button activated a receiving trigger box and simultaneously sent a spike to the Vicom system, which was recorded along with the motion data to aid with synchronisation during analysis. The trigger box receiving the signal from the wireless button directly triggered the EMG and high-speed video systems and set off the Tekscan trigger box. The Tekscan trigger box triggered the Tekscan system through a serial connection not present on the receiving trigger box. The Signal Calc system was also triggered from this box through a standard BNC cable to reduce the number of connections to the receiving trigger box. All trials were captured on high-speed video synchronised as shown in the schematic.

For the purposes of monitoring accuracy and to provide the player with a visual aid a target area of 1.350 m by 1.025 m was marked out just inside the previously marked baseline. The player was instructed to hit all shots towards the target area. The test began by allowing the participant to hit some balls fired from the bola ball machine as a warm up and as a form of familiarisation. The player was asked to hit slice backhand shots with a racket marked up with Vicon markers. The markers were very lightweight polystyrene balls and the racket was otherwise un-instrumented so matched the original racket as closely as possible. This allowed the player to hit relatively uninhibited shots whilst capturing dynamic motion data. Once a number of satisfactory trials were successfully captured, the player was asked to repeat the test hitting backhand topspin drive shots.

The racket was then replaced with the Tekscan racket and the process repeated with both slice and topspin backhand shots. Subsequent trials were conducted with the fully instrumented racket. The whole protocol was repeated for both the LM8 and the Prestige rackets (Glynn, 2007).

5.4.6 Wired System Performance

The wired system design solution performed adequately or exceeded the design specification in the following areas:

- **Measure types:** all 6 degrees of freedom and grip pressure measurement
- **Resolution and sample rate:** Signal Calc has a 24 bit resolution and is capable of sampling at up to 20 kHz
- **Period of Capture:** The system is mains powered and only limited to the capacity of the computer's hard drive.
- **Size Weight and Ergonomics:** the system did not alter the external dimensions of the racket in anyway
- **Installation Changeover and Maintenance:** the wired system was easily accessible and constructed on the most part from readily available off shelf components allowing for ease of maintenance and replacement of parts

The wired system solution failed to meet the design specification adequately in the following aspects:

- **Resolution and sample rate:** Tekscan is an 8 bit system only capable of sampling at up to 220 Hz
- **Size Weight and Ergonomics:** the system mounts weighed a little over the 100 g minimum required level and added over 120 $kgcm^2$ to the inertia of the racket which, although still appropriate for the validation of a computer simulation of the player, was unacceptable within the design context for the purposes of this research.
- **Aesthetics:** the additions of the mounts, sensors and wiring cause significant visual distraction and interference with perceptions
- **Installation Changeover and Maintenance:** although the mounts could be installed and removed relatively quickly, applying grip tape and the Tekscan sensor took upwards of 20 minutes.
- **Adaptability:** the uni-axial throat mount was able to fit a number of racket frames but the tri-axial insert mount was only compatible with the (since discontinued) light weight racket range with one piece construction allowing more space in the racket butt.

Clearly the system, although capable of providing a range of important simultaneous measures is compromised in its successful application by wired data acquisition and an overly intrusive uni-axial accelerometer mount design, leaving significant scope for improvement with regards to primary research question (Section 5.1).

5.5 Prototype Wireless Design Solution

5.5.1 Prototype Wireless Data Logging Electronics

As noted in section 5.3.3, development of the wireless design solution hinged on the provision of a custom data acquisition device supplied by BTI. BTI were asked to develop a system in accordance with the design specifications listed in section 5.3.3. The fundamental solution adopted by BTI was to provide:

- Rechargeable battery powered electronics in a package small enough to fit within the dimensions of a Head racket grip (23 x 14 x 185 mm).
- Single switch manual activation.
- Single switch manual reset.
- USB 2.0 compact data connectivity to Microsoft Windows Compatible PC for setup and data download.
- Onboard data capture functionality, signal conditioning, analogue to digitial conversion, buffering up to 4 hours and threshold based triggering.
- Built in tri-axial capacitance based accelerometer, 3 uni-axial piezoelectric accelerometer compatible channels, 2 piezoresistive FlexiForce compatible channels.
- PC software to preview data and configure the systems sample frequency, resolution trigger level, capture duration and pre-trigger capture time.

The first version of the device that was received from BTI was packaged in a box that was far too large (50 x 62 x 16 mm) to be mounted on or within a racket frame (Figure 5.9). The device was, however, small and light enough to be mounted on the wrist of a player, which allowed for much more freedom of movement. The expensive Model 23 tri-axial piezoelectric accelerometer from the wired system was replaced with an on board capacitance based tri-axial accelerometer. The Tekscan sensor and bulky cuff was also replaced by two Flexiforce sensors connected directly to the device. The Bruel and Kjaer model 4375V uniaxial piezoelectric accelerometers remained in the wireless system, but with the data logger more local to the accelerometers, the 10 m cable extensions were no longer required.

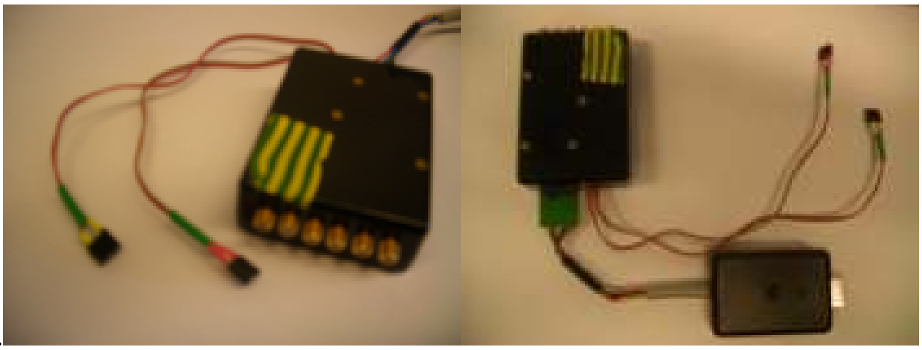


Figure 5.9 Wireless device data logger first iteration

Pilot testing revealed that the data captured from impacts often overloaded the device and was generally very noisy with lots of unwanted high frequency background noise in amongst the signal. Recommendations were made on the basis of preliminary trials to adjust the sensitivities of each of the wireless channels and to introduce low pass 350Hz filters to reduce the noise and aliasing in the signal.

BTI made the appropriate adjustments to the system based on the recommended specifications and the returned device was again pilot tested. The results of the test were encouraging, with the signal looking both cleaner and very rarely overloading.

5.5.2 Prototype Testing

This revised system was utilised effectively in two undergraduate studies. One of these was a perception study that investigated the ability for players to detect changes in moments of inertia between rackets. Four identical racket frames weighted to have extremes of mass and moments of inertia within the market range were adapted to accommodate various forms of instrumentation. The throat bracket was still used to mount the uni-axial accelerometers. The plastic sleeve and insert were also still employed to mount the tri-axial accelerometer inside the hollowed out handle of the Head light weight range rackets. FlexiForce pressure sensors were placed under the grip to measure the grip response at the base of the proximal phalanx of the index finger, and at the hypothenar eminence.

A Lobster ball machine was used in the test to feed balls to the player. The ball machine was situated opposite the player and fed balls straight to their forehand side. Crosscourt from the player a target area was marked out with tape and marker cones

The test protocol began by asking the participant to warm up with a control racket, in this case a Head Ti Radical. This warm up process was done using the ball cannon set up for the test and thus acted to familiarise the player. The player was shown a pre-prepared questionnaire to familiarise them with the questions so they had an indication of what racket characteristics they should be most aware of during the test.

The physical data collected from the perception testing appeared to be adequate, unfortunately player feedback suggested the weight of the BTI device on the players' arm interfered significantly with the their perception of the rackets inertia and weight, distorting any possible conclusion that might be sort from the testing. This realisation emphasised the need to further develop the system so that it might be less intrusive to the player.

5.6 Final Wireless Design Solution

5.6.1 Introduction

Two features of the prototype system were identified as seriously compromising design success:

- The data acquisition electronics were too bulky to embed in the racket requiring limited but disruptive wiring.
- The packaging of the equipment, although relatively small and light, inhibited player perceptions mounted on the forearm
- The uni-axial accelerometer mounting solution was too bulky and heavy.

Delivery of a markedly improved second generation data acquisition electronics from BTI provided the opportunity to address the first 2 issues. Exploitation of rapid manufacturing facilities within Loughborough University provided the means to address the third issue. All are described more fully in the following section.

5.6.2 Second Generation Wireless Data Acquisition

BTI redesigned the electronics layout so that the data acquisition unit could be fitted into the grip of a tennis racket To provide enough space for the device the central dividing wall of the hollow in the grip was removed (figure 5.10). With this complete the device could be observed firmly secured in the hollow so that it would not move or vibrate with respect to the frame in the course of any testing (figure 5.11). The second generation wireless data acquisition hardware had the following specifications:

- **Measure types:** with in built tri-axial accelerometer, 3 channels for uni-axial accelerometers and 2 channels for FlexiForce sensors the system was able to achieve 6 degrees of freedom and grip pressure measurement
- **Resolution and sample rate:** 12 bit resolution and up to 3277 Hz sampling rate
- **Period of Capture:** 4 hour capture time
- **Size and Weight:** the hardware weighed around 20 g and was contained in packaging small enough to fit within the racket butt (23 x 14 x 185 mm)

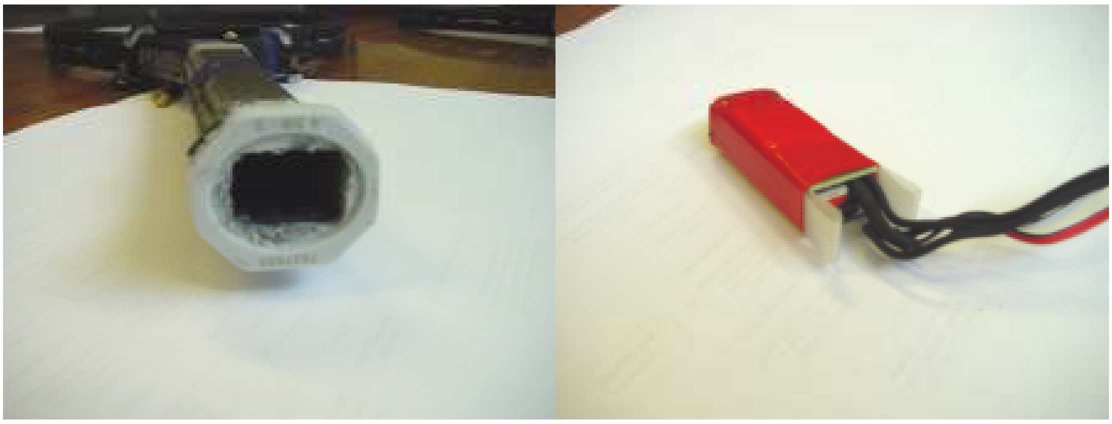


Figure 5.10 Hollowed racket butt and final iteration of the wireless data logger

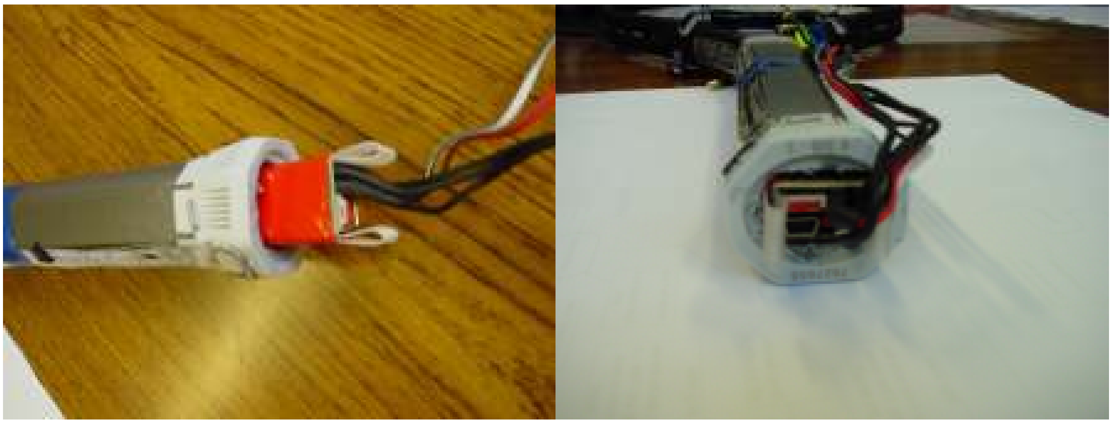


Figure 5.11 Wireless data logger mounted inside racket butt

The final iteration of the BTI data acquisition hardware was significantly smaller and lighter than its predecessors, utilising the latest developments in battery technology and compact printed circuitry. The new system was light enough that the inertia properties of the racket were not significantly affected. This development has a significant impact on the application of the device, since a large proportion of the instrumentation required for racket testing could be concealed from the player, reducing the impact on the player's freedom of movement and perception of the racket.

The choice of method for the wires of the device would affect how the device and the associated instrumentation could be mounted. The first factor to be considered was that of protecting the wire junctions which were most vulnerable to noise. Running short wires off the device would probably entail a connection hanging from the bottom the racket butt cap, from which the accelerometer wires could be run under the grip up to the throat. This would have meant that the junctions would be easily accessed, allowing for a quick and easy removal of the device if it needed to be switched for another device or put into another racket for a different test. Although this option did seem attractive, the relatively exposed position of the junction meant that the signal would be more vulnerable to noise and the option of moving the device from one racket to another seemed less useful if only one set of accelerometers was available (as in this case) since these had to be moved as well.

An alternative option was to revise the mount so that the junction could be housed in with the accelerometers, protecting it from movement and damage. This would allow more flexibility in the positioning of the instrumentation and would conceal it better from players, reducing its impact on their perceptions.

The other remaining method led the wires under the grip up to the throat, where the junction could be secured to the racket frame which could act to support and protect it. This was decided to be the most suitable option since it was easy to achieve and allowed for flexible application, with wiring that could be adjusted to suit a variety of mounting methods.

5.6.3 Instrumentation Mount Development

The original mount employed an aluminium clamp secured at the throat onto which the accelerometers could be attached. This clamp was relatively heavy and made the racket somewhat ungainly, and certainly affected players' perceptions of the racket both visually and in their sensation of the inertia properties of the racket.

To attempt to address these issues a number of alternative mounts were considered:

- A lighter weight version of the existing mount that could be made from carbon fibre and coloured black to reduce its visual impact
- A mount positioned lower on the racket closer to the grip that could be smaller and lighter and would less impact on the rackets inertia
- An integrated mount that would be formed as part of the racket in which instrumentation could be concealed within the grip and butt cap

The lighter weight carbon fibre version would provide the same quality of data as the original mount, and would reduce the undesirable effects of its weight. By colouring the mount black the visual distraction of the mount would also be minimised however the change to the racket shape would still be prominent, and although reduced the effect of the additional weight would still be evident. Perhaps more importantly, the area of grip interaction is of primary interest although convenient and able to accommodate larger offsets from the tri-axial accelerometer the throat mount is perhaps too remote from the grip to give accurate angular degree of freedom results.

A new mount devised to fit just above the racket grip would further reduce the affects of the weight of the mount due to the reduced moment force about the grip as well as allowing the system to directly measure effects at the grip section of the racket. The racket is thinner at this section of the racket and so the size and visual impact of the mount could also be significantly reduced. Unfortunately, with the accelerometers closer to the internal accelerometers, the accuracy of the data could potentially be reduced with errors and inaccuracies effectively magnified. Although most of the testing in the current study involved one handed shots, this mount could potentially interfere with any double handed shots.

An integrated mount would still suffer from the reduced accuracy of data in terms of tri-axial accelerometer offset, but would not interfere with a double handed shot in the same way. Furthermore, the increased error due to reduced offset is arguably diminished by the increased accuracy with local grip angular moments measured without the errors introduced by the intervening frame modal response.

One added advantage of an integrated mount, with all the instrumentation housed in one unit, is the potential to quickly and easily switch it between rackets. The whole grip surface will then also be consistent between rackets, improving the comparison of grip pressure data as well as maintaining the feel to the player.

Calculations to determine the extent of the change in data quality revealed that the difference will be subject to a proportionally higher margin of error compared to that from the original mount. The resolution of the data acquisition system encompassed an error of approximately ±0.001 ms^{-2} which, with the difference in the distance between the mounted accelerometers of about 60%, equates to a relative increase in error of ±0.0006 ms^{-2} which was considered to be acceptable particularly when the considerable benefits of this mounting system were also taken into account.

Consequently an integrated mount was designed to replace the PU foam grip sleeve and butt cap of the racket as shown in figure 5.12. A larger bulbous end to the butt cap allowed space to house the three uni-axial accelerometers and the associated wiring for the rest of the device as is shown in figures 5.13 and 5.14. Wires for the uni-axial accelerometers were run up the grip where the junctions could be fitted into small holes that would help support and protect them reducing the potential for noise generation and leaving more space in the bulbous butt cap for other wiring (figure 5.12).

5.6.4 Calibration

Before testing could begin much of the test equipment required calibration. The Bruel and Kjaer, 4375V uni-axial piezoelectric accelerometers were pre-calibrated and in good condition. Using a laser vibrometer, a signal generator and a freely suspended shaker it was possible to verify that the calibration of the uni-axial accelerometers was consistent with that indicated.

The same rig was planned to be used to calibrate the wireless data acquisition hardware, but a failure with the laser meant that the vibrometer was unavailable in the time scale required, so an alternative jig was constructed that utilised one of the pre-calibrated uni-axial accelerometers as a reference in place of the laser vibrometer.

The rig required a mount to house the wireless data acquisition hardware which was attached via a sting to a KCF electromagnetic shaker, all of which was freely suspended from a steel frame. A pre-calibrated uni-axial accelerometer was attached via a rigid sting to the mount housing the wireless device. A signal generated using Signalcalc software on an IBM compatible laptop computer to drive one of the output channels on a Dataphysics PCMCIA data acquisition card. The wireless data acquisition hardware was activated and simultaneously recorded the signal received from the transducer in question. The calibration jig was arranged as shown in figure 5.15.

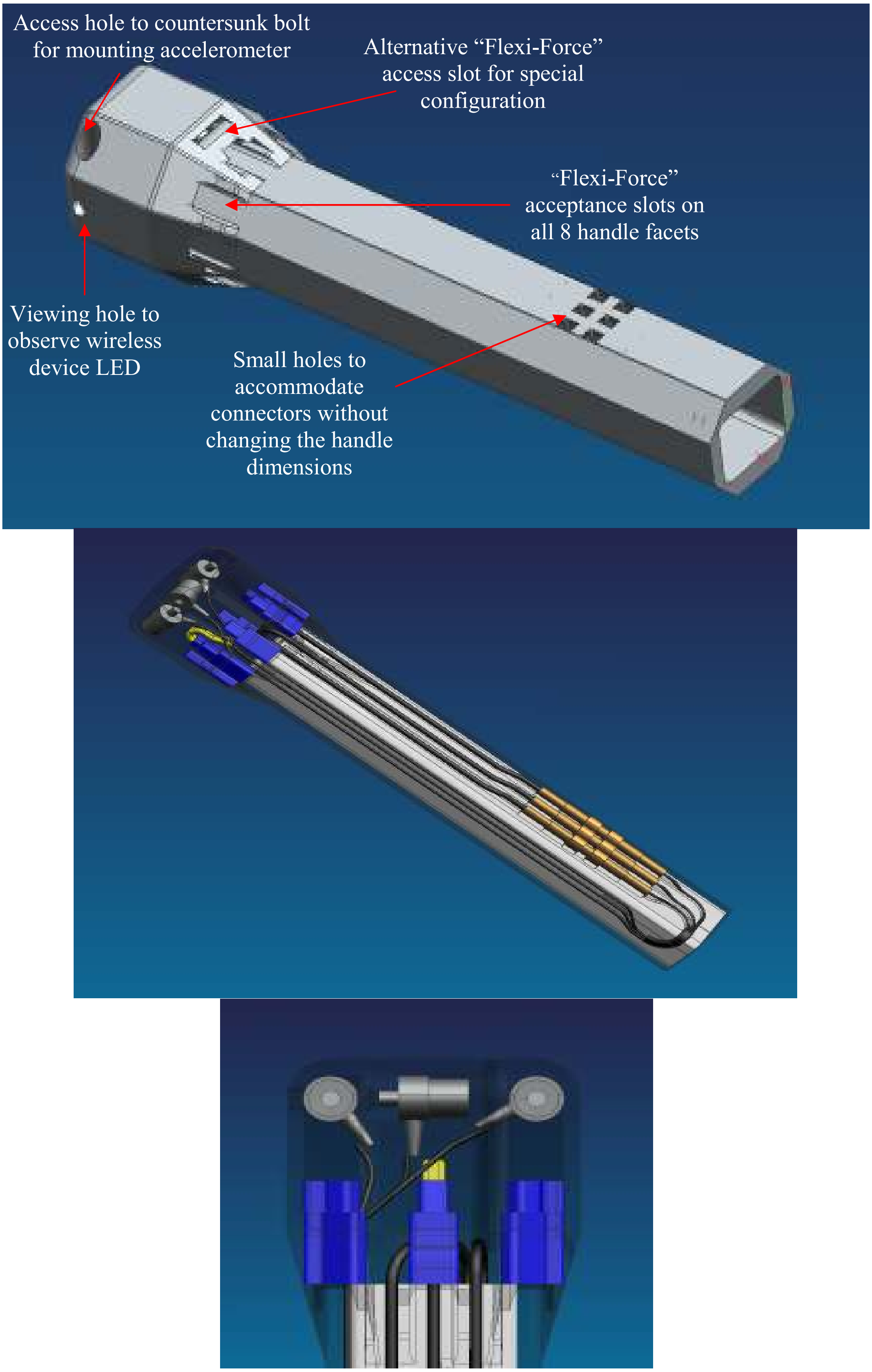


Figure 5.12 CAD rendering of instrumentation mount and transparent images showing wiring and instrumentation

Figure 5.13 Final iteration of the wireless instrumentation system without grip tape, displaying FlexiForce Sensor locations

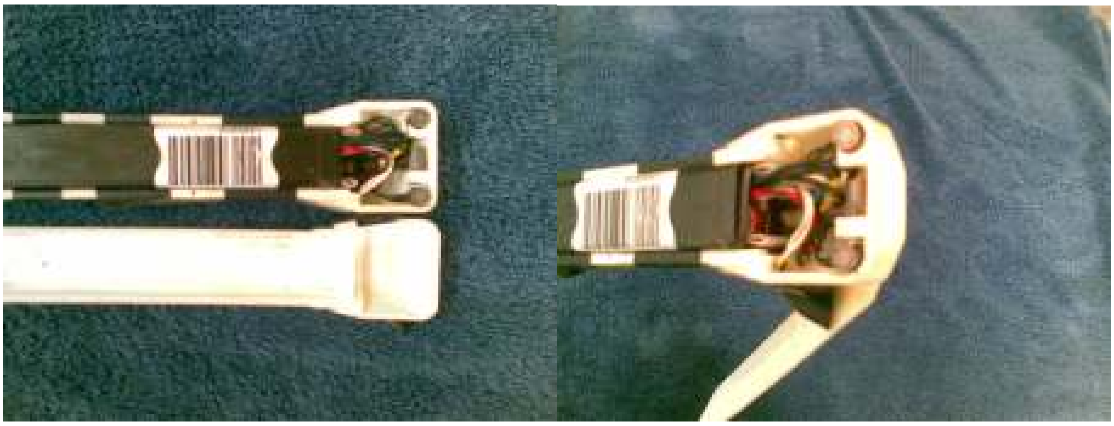


Figure 5.14 Fireless instrumentation system mount open displaying arrangement of accelerometers, wiring and data logger

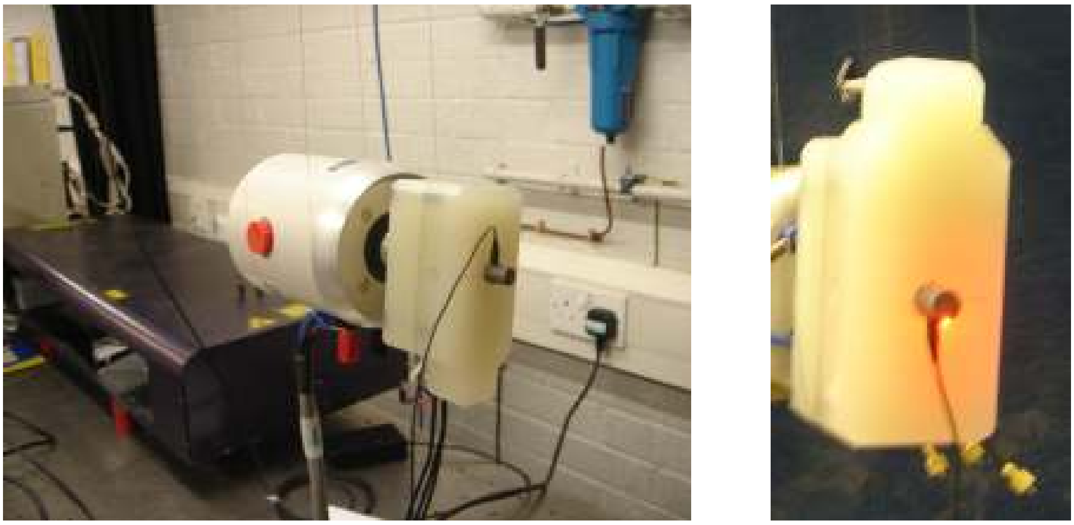


Figure 5.15 Wireless data acquisition hardware calibration test jig

The signal generated was chosen to be in the range that would be expected from testing. The approximate modal frequencies of the racket (Brody, 2000) were simulated, and amplitudes up to and above those that had been reported in related work (Bowyer, 2003). The comparison between the Signalcalc data and the data from the wireless data acquisition hardware produced a calibration curve similar to the example shown in figure 5.16 for each separate channel.

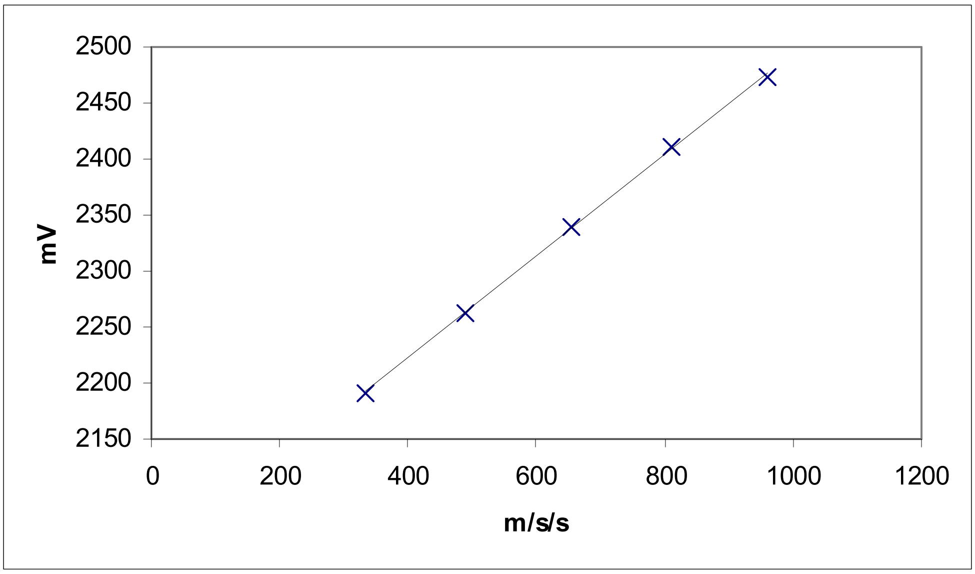


Figure 5.16 Typical example of a single accelerometer channel calibration curve

A separate test was required to calibrate the Flexiforce pressure sensors similar to that used by Schmitt (2007) as shown in figure 5.17.

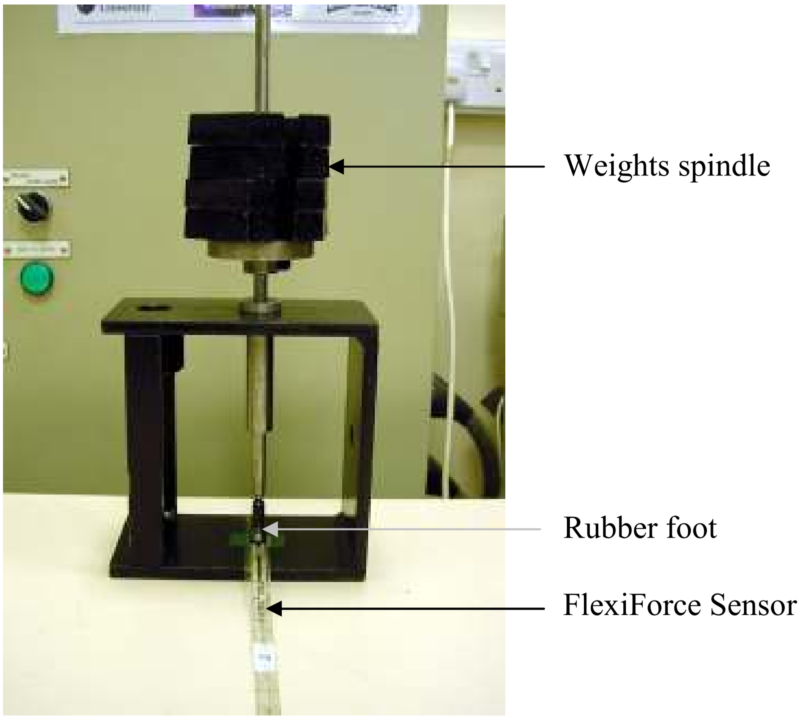


Figure 5.17 FlexiForce calibration test

Known weights were added to the custom sized foot and the sensor response was recorded and compared to the added amounts of weight. Weights were incremented to mimic the forces that might be experienced during testing and a calibration curve was plotted from the results. Due to the elastic nature of the sensor it was potentially vulnerable to hysteresis effects so a calibration curve was plotted for both loading and unloading of the sensor (figure 5.18).

Figure 5.18 shows that although there does seem to be some evidence of the effects of hysteresis, the difference in the gradient and offset of the loading and unloading trend lines are still very similar.

Throughout calibration the device captured data that was clear and decipherable, and an appropriate calibration curve was calculated for both channels on a main and back up device.

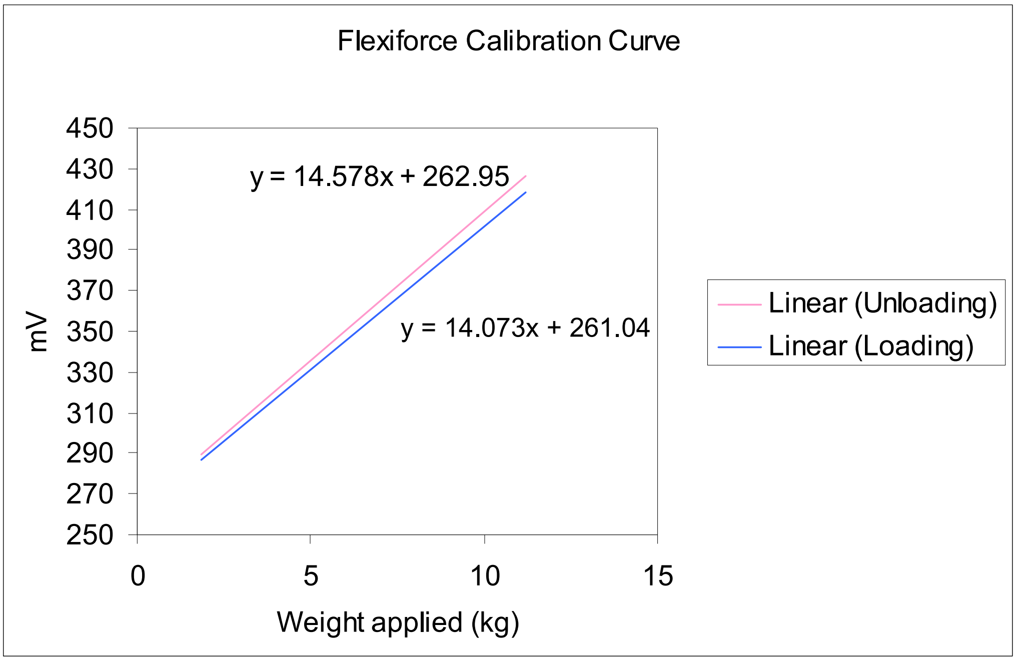


Figure 5.18 FlexiForce calibration curve

5.6.5 Preliminary Testing

At the higher capture frequencies, suggested by BTI to limit any aliasing and increase the chance of being able to capture peak values, the captured signal displayed unusual flats and steps. BTI confirmed, as suspected, that these flats were due to the limited buffering capacity of the device, and suggested that the capture rate be reduced or less channels be used to eliminate this problem. Since all the channels would be required during testing a series of experiments established that the optimal sample frequency for capture, without inducing the, afore mentioned, flats, was 2979Hz.

Further testing was conducted to ensure that the wireless system was robust enough to survive extended tests. A top 50 ranked English national player was asked to hit a range of shots, including sets of high power shots such as serves and volleys, and point play rallies for a duration of approximately 30mins. Analysis of the results revealed that the device had overloaded in two cases. These were suspected to be serves or volleys that hit the frame, and were clearly not typical of the type of data that would normally be recorded. The device was actively capturing data for the full test and the majority of the impact data lay in the optimal voltage range. The individual impact traces were comparable to those recorded previously using other methods of capture, demonstrating that the newly implemented bandwidth filters were effective in reducing noise without loss of signal. Figure 5.19 shows some typical accelerometer traces from each channel.

In some cases the grip force signal resembled that which might be expected from grip force data, such as the case in figure 5.20 (a) and (b). It was tempting to try and filter out some of the noise to make use of this data, but it was clear that in the majority of cases the noise overwhelmed the signal as can be seen in figure 5.20 (c) and (d). Although the underlying trends are suggested to the human eye, the chaotic disruption in the signal as it seemingly toggles between two separate calibration levels renders the data useless except to confirm that grip force levels were generally similar to those published elsewhere (e.g. Bowyer, 2003, Knudsen 1988).

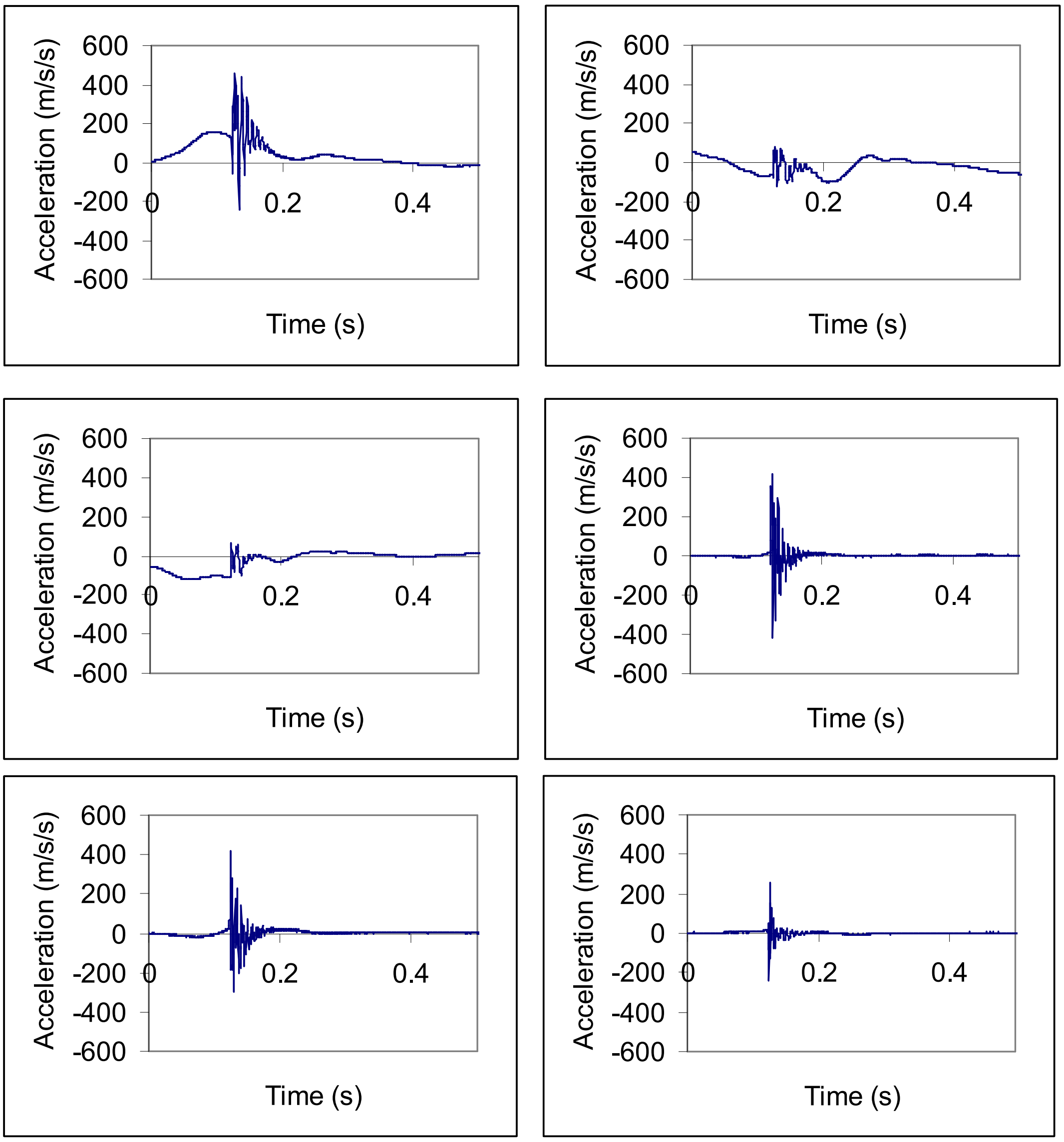
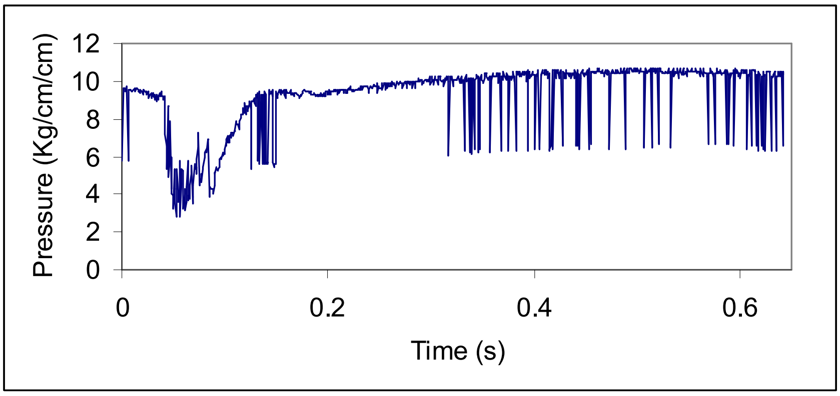
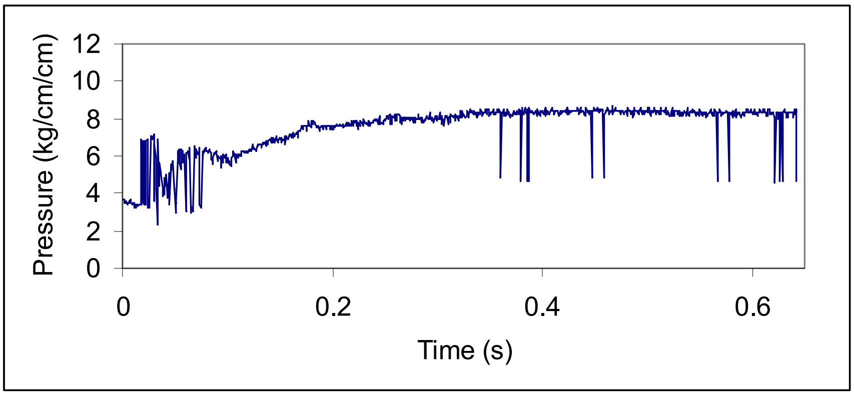


Figure 5.19 Typical impact traces from all 6 accelerometer channels

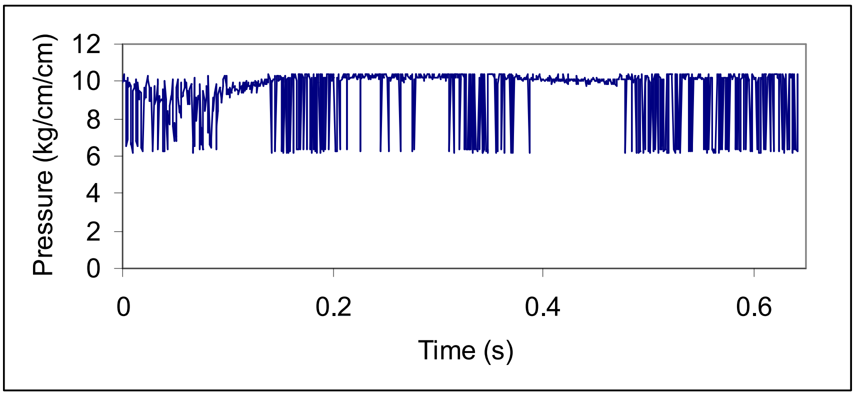
(a)



(b)



(c)



(d)

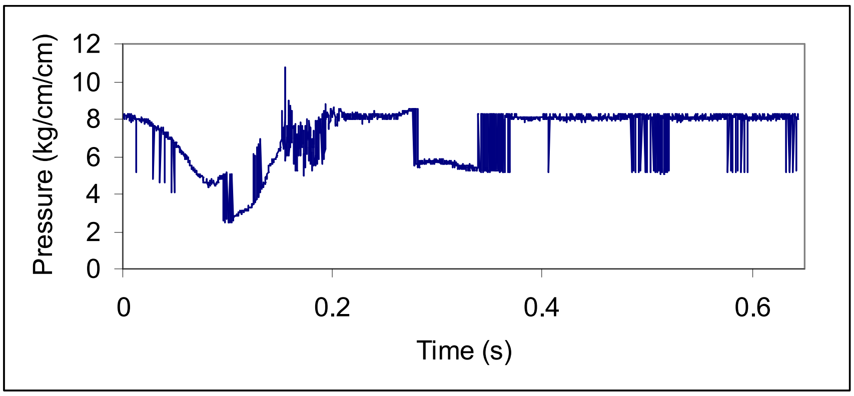


Figure 5.20 Typical noisy grip force signal traces

Some repeated instantaneous drops and gains in the signal can be observed that appear at times to be periodic with a frequency of approximately 50 Hz. Much of the noise appears to be somewhat chaotic, in as far as periodic noise appears to randomly appear and disappear on the trace and at times when less periodic noise is present the whole signal appears to be offset for a time before returning to its original level. The unusual shape of the trace suggests the data is corrupted or at least subject to a severe degree of interference. The unpredictable and binary nature of the noise also makes it extremely difficult to filter out.

The calibration, as described in Section 5.6.4, was conducted under static conditions with weights added and removed from the sensor accordingly. Once calibrated, pilot tests were conducted and the resulting noisy traces observed. It seemed the more dynamic conditions had an adverse effect on the data capture. The problem was present on both FlexiForce channels and in both the main and back up devices suggesting that this was a result of a hardwired design weakness rather than a manufacturing fault or failure. Consultation with the manufacturer, BTI, led to some speculation about the problem being associated with interference from the flashing LED or signals from the other transducers, but ultimately could not resolve the problem in time to meet the planned testing window.

5.6.6 Final System Evaluation Against the PDS

The features of the final wireless system design was compared to the original PDS to determine the level of success achieved. The details are presented in tables 5.3 to 5.9. The hardwired elements of the system were deemed to be successful and achieved a full set of acceptable, and some cases ideal, rating levels. The level achieved by the device is highlighted in bold in each case:

Table 5.3 performance specifications

12 bit resolution achievied	• **12 bit resolution required for an acceptable 0.1% error range at 25% of the full scale**
Sample rate of 2700 Hz achieved	Angular and linear accelerations: • **A sample rate of around 1000 - 2000 Hz would be suitable since frequency analysis will be possible and samples per peak will be sufficient for peak to peak values to be assessed to some degree of accuracy** • **Ideally the sample rate would be more than 2000 Hz so as to be able to examine the finer details of grip response to vibration**
Capable of a 4 hour period of capture	• **Ideally the total capture time would exceed 3 hours for optimal flexibility, multiple tests and to allow for margin of error considerations.**

The device interface was not capable of real time data transfer which meant that early detection of problems that occurred with the system was not possible. In practice, early detection would have proved useful in a few cases, but on the whole the system behaved normally and the USB interface was perfectly adequate.

USB interface for data collection and analysis	• **Given the large amount of data expected, the system will have to be able to transfer data to a computer in a Microsoft Excel readable format**. • monitoring of the data.

Table 5.4 Size, Weight and Ergonomics Specifications

Adding the system to a racket inevitably changes its characteristics to some extent. The wireless system was, however, designed to minimise these effects as indicated by achieving at least an acceptable rating for all aspects

33% added weight	• **An increase of between 10-30% would be acceptable since this would put the racket well inside the market range and allow for a reasonable test range**
3.5 cm added Length	• **An increase of less than 2cm be acceptable since this would keep the racket well within the extremes of the market range**

The relatively small moment of inertia added to the racket proved to be particularly beneficial in the later full scale perception testing.

3.3% increase in moment of inertia	• **An increase of between 1 – 15 % would not change the racket too dramatically and allow for a large test range so would be acceptable**

Table 5.5 Durability Specifications

A battery life of upto 24 hours	Battery life	• **Ideally the battery life would exceed 4 hours at a time to allow testing to continue for a day at a time without the need for a recharge**

Table 5.6 Installation, Changeover and Maintenance Specifications

The simple and all-inclusive nature of the system made it easy to install, change over and adapt to fit different rackets. These qualities also made for easy maintenance.

Can fit any standard Head racket	Adaptability	• **A system capable of fitting any of the Head racket range would be acceptable since this could be utilized for 'in house' testing and comparison between racket designs.**
Change over time takes approximately 3-4 minutes	Installation/ Changeover time	• **An installation or changeover time of between 1 and 5 minutes would be acceptable since this would be able to be easily implemented into a protocol time line**
Requires maintenance after a days testing as some sensor may need replacing	Maintenance frequency	• **Daily maintenance would be acceptable since this would allow for a full days uninterrupted testing**
Maintenance generally takes about 5 minutes to check and replace sensors	Maintenance Duration	• **An acceptable maintenance time would be between 1 and 5 minutes since this would be able to be conducted quickly without significantly affecting the test schedule**

Table 5.7 Aesthetics Specifications

Aesthetics – unnoticeable except for bulbous addition to butt cap	• **A discrete masked change to the overall appearance shouldn't distract the participant or interfere significantly with their perceptions so would be acceptable**

Table Manufacturing Process and Materials Specifications

The materials used in the manufacture were generally 'off the shelf' with a custom built mount	• **Limited innovation and 'off the shelf' solutions would be an acceptable method of producing a system within the available time whilst meeting the design specifications**

Table 5.8 Testing Specifications

Calibration process was lengthy but only required for each new study	• **A system that is simple to calibrate and need only be recalibrated at the end of each study would be acceptable**

Table 5.9 Production Specifications

Quantity – 2 were constructed with the extra one serving as a back up device	• **Ideally multiple devices would be produced to serve as back up to the one in use, and to provide an option for multiple rackets for quick and easy change over, or multi-participant tests.**

5.6.7 Performance in Use

The device was put into full operation in a test investigating the effect of fatigue on the player (Chapter 8). The test involved the player running back and forth along the baseline and was only possible due to the improved qualities of the new device. A few weeks into testing the device began to behave unusually, shutting down part way through tests and occasionally corrupting the captured data. The problem became progressively worse until the device finally failed completely. In response to a report of the failure, BTI suggested that it may be due to a battery cell failure that may have experienced accelerated fatigue because of continual charging and discharging.

Testing continued with two replacement devices, that ultimately suffered the same fate. The devices were returned to BTI for more extensive diagnoses that revealed that the BIOS in each of the devices had been corrupted. Further investigation by BTI led them to conclude that when the battery power fell below a threshold level the BIOS was interrupted as the device shut down. BTI reprogrammed the device to protect the BIOS when the battery life became low. The revised device was again used in testing, this time investigating the relationship between players' perceptions and physical measures off a racket. The reprogrammed system proved to be more robust and allowed the completion of this study

5.7 Summary

The wireless device was developed to broaden the application of the instrumentation system and attempt to reduce the impact on the player and thus the results. The alternative wired version of the system restricted the range from the computer system of the player to the length of the 15 m wires, and encompassed an aluminium bracket which significantly altered the inertia of the racket. The first version of the wireless data logger system was encased in a small size box that could be strapped to a player's arm. The boxed system gave the player much more freedom of movement, but the inherent weight of the box on the arm still distorted the players' perception of inertia properties, and was very conspicuous and potentially distracting. The data collected from this system was also fairly noisy and some recommendations were made to introduce some filters and adjust the sensitivities of some of the channels to improve the signal conditioning. Further refinements to the system saw the development of a wireless device that was small and light enough to be inserted into the grip of a racket so was well concealed and had less impact on the player, as well as offering new mounting options for the associated instrumentation.

To maximise the benefits of the new wireless device a revised instrumentation mount was developed that would replace the grips outer covering PU foam and butt cap. The newly integrated mount and grip was light weight and concealed all the instrumentation within the grip sleeve and a bulbous ‘butt cap’ end. This provided support and protection to the wires, sensors and transducers and minimised the influence on the player.

The newly developed device was used in testing for a number of weeks before a further fault emerged. The device was failing when the battery level fell below a threshold level which caused the BIOS to be corrupted, rendering the device useless. The fault was corrected by amending the programming so that the BIOS would be better protected at these lower battery levels. In spite of these problems the revised device was instrumental in allowing the capture of ‘in play’ data, allowing the freedom of movement required to run full body fatigue tests and being light and inconspicuous enough to run perception tests with out a significantly influencing the results. Testing was eventually successfully completed and the results exported and analysed for use in the research.

Substantial improvements have been made from the first iteration but the final version of the wireless system still has some faults, namely the grip force channels are ineffective and the device still experiences some reliability problems at present. However, it has been clearly shown to be a very useful development for the research, greatly increasing the diversity of possible protocols able to take physical measures from the racket. Chapter 6 and Chapter 8 demonstrate the full extent of the benefits of the system in experimental tests investigating player perception and fatigue respectively.

CHAPTER SIX

PERCEPTION TESTING

6.1 Introduction

With the perception relationship model (feel map) fully complimented by the questionnaire results and the weighted lexicon, its application could be explored. It was first used to develop a test questionnaire which could be used to investigate players' perceptions of selected racket characteristics. The development of an unobtrusively instrumented tennis racket provided a new opportunity to collect physical data without impinging on players' perceptions or ability to play a natural stroke. During research tests the questionnaire was used to compliment the physical measurement data sets enabling the investigation of the research question:

> Can a relationship be established between players' perceptions and physical measures detected from changes in racket characteristics?

The results of such an investigation have important implications for commercial racket research. The results help to indicate how reliable player feedback can be in the development of new racket technology. The racket characteristics players are most sensitive to could also be revealed. This information should help indicate which racket designs are most effective in achieving optimum 'feel' for a player. Further to this, it may be possible to relate some range of physical measure to players' questionnaire feedback, which might be used as a cheaper and quicker method of initial prototype testing and refinement.

To begin to answer the proposed research question a hybrid experimental study simultaneously gathering subjective and objective measures was needed. The first problem in describing such as study is to limit the scope to a manageable level. The previous Chapters (3, 4 and 5) outline the breadth of feel perception (12 principle dimensions) the degree of sensory confusion or interdependency and the range of the physical design characteristics and racket performance phenomena. Clearly a study that attempts to address them all simultaneously and establish correlations between them is unmanageable. A more achievable objective would be to study one feel dimension and monitor the effect of a range of design characteristics/performance phenomena on perception. Another would be to vary a single design characteristic and monitor the affect on performance and feel perception. The later approach was chosen as the basis for the study reported in this chapter to avoid the difficulty and expense of engineering too wide a range of alternative and distinctly different designs evenly distributed in the potential design space. Obviously to completely understand all the potential correlations between feel perception and characteristics/phenomena several studies limited in this way are needed.

This approach is however more difficult than first stated since few of a racket's design characteristics are fully independent (i.e. can be varied without affecting others). In the remainder of this chapter a suitable experimental study is presented based on the variation of racket moment of inertia, since it is argued to have least affect on other characteristics and has traditionally been a priority for consideration by players, coaches and manufacturers. It is also relatively straight forward to vary. Other elements of control introduced to the test included selecting players that could use the "semi western" tennis grip, using a ball cannon to feed the ball consistently and using newly opened tins of balls of the same type for all tests.

Testing was conducted with a sample of 20 players, all with high levels of playing experience. In Chapter 3 and Chapter 4 the extensive development of a 'feel map' is discussed from which a test questionnaire was developed. The questionnaire was designed to use vocabulary and language familiar to experienced tennis players to try and limit misinterpretation and maximise understanding. In Chapter 5 the development of a wireless data logging system and associated mounts was discussed. The wireless instrumentation and mount allowed measurements to be taken 'in play', with the player able to freely perform as uninhibited as possible. The results are presented and discussed in Chapter 7.

6.2 Methodology

6.2.1 Choice of Racket Design Variable

Three factors were considered when selecting the most appropriate design characteristic to vary:

i. Independence from other characteristics
ii. Ease of implementation
iii. Priority for beneficiaries (i.e. players, coaches and manufacturers)

Regarding ease of implementation to have the ideal scenario would have been separate racket frames custom manufactured to vary a single characteristic with each separately instrumented to allow quick and easy changes between test sets. This scenario was clearly not logistically possible given the time and costs involved in producing customised rackets. Further to the logistical problems custom racket production alone posed, producing multiple wireless data loggers would have incurred further delays and exacerbated the reliability issues already experienced with the device.

The alternative design characteristics considered included frame flexibility, moment of inertia, length sound, string tension, post impact vibration levels and weight. Table 6.1 lists each of these against a method proposed to achieve variation with minimal effect on other properties. The unwanted effects are also tabulated and each alternative awarded a score on this basis. For example the weight of the racket could be changed by adding lead weights at several points around the frame. Correctly sited the affects on moment of inertia could be minimised but the affect on sound, post impact vibration and even the racket aesthetics was likely to be more persistent.

Table 6.1 Effects of adjusting selected characteristic variables. ● *= large effect* o *= moderate effect*

Characteristic	Characteristics Affected									Effect of Implimentation
	Method of Variation	Flexibility	Moment of Inertia	Length	Sound	String Bed Stiffness	Vibration	Weight	Visual Impact	
Flexibility	Change racket frame	●	●	●	●	o	●	●	●	Changing racket frame expensive and time consuming
Moment of Inertia	Attach and move lead weight		●		o		●		o	Visually detectable
Length	Change racket frame	●	●	●	●		●	●	●	Changing racket frame expensive and time consuming
Sound	Change string tension/ dampening	o			●	●	●			Requires multiple frames difficult to vary
String Tension	Change string tension or string	o			●	●	●			Requires multiple frames
Vibration	Change frame stiffness/ dampening	●			●		●			Difficult to implement and control degree's of variation
Weight	Add lead weight				●		●	●	●	Visually detectable

Table 6.1 shows that varying moment of inertia or vibration characteristics has the potential for the fewest undesirable side effects, followed by sound and string tension. The table shows that the most independent methods are those attempting to vary moment of inertia, sound, string bed stiffness and vibration. Modifying all of these affect post impact vibration to some degree, but without the expense of deliberately engineering several racket frames to maintain the same modal response whilst the primary variable changes (if this were possible) the effect is unavoidable. However, with a single frame material being used these effects should not be too substantial (Jandak, 1993). Once the easier to isolate characteristics are better understood their effect on performance phenomena in concert with the less easy to isolate characteristics changes can perhaps be accounted for.

The variability of post impact vibration response itself presents a serious problem if this is achieved by varying the stiffness and damping levels. Although piezoelectric chip set systems are effective in damping the frame (Kotze et al. 2003), variation would require changing the electronics to vary the gain settings to several different levels in separate frames or additionally changing the construction to allow adjustment between tests. Head Tennis AG were unable to support the research in this way.

To change string bed stiffness in a single frame required the strings to be cut out and the whole racket restrung. Besides the problems associated with bedding in new strings, restringing a racket several times during a test would be too time consuming for the method to be practical. Alternatively several identical frames would have been strung at different tensions and the instrumentation swapped between them. Difficulties with the wireless data acquisition device robustness and the time taken to reposition FlexiForce sensors made this option unattractive.

The methods proposed for changing the sound are the same as those for vibration response or string bed stiffness with the added possibility of damping the string bed to affect its sound. It is possible to add dampeners to the string bed, and although challenging to do so, this level of damping could be varied to some degree. However, it is difficult to objectively assess or measure the sound made by the racket as perceived by the player since it is also affected by many other variables that are difficult to control; the speed at which the strings are impacted, the impact locations and the angle of impact could all change from shot to shot, and all would produce different sounds.

Moment of inertia was a variable that could easily be changed without substantially affecting other controlled experimental elements. Lead weights added to the frame could easily be moved and secured to predetermined positions on the racket that would increase and decrease the racket's moment of inertia appropriately without affecting the overall racket weight. To tackle the affect on the visual aspects of the racket characteristics the racket was lacquered black and the additional lead tape was concealed as best as possible by black adhesive PVC tape.

In addition to the convenience that moment of inertia poses as a choice of variable there is considerable anecdotal evidence from coaches and players that suggests that moment of inertia is an important element to be considered when selecting a racket. It is a racket quality frequently mentioned early on by players in the interview testing described in Chapter 2, which suggests that players are familiar with the concept of assessing the moment of inertia. When considered mechanically it is clear that a change in the moment of inertia should have some affect on performance when all other elements are controlled, e.g. input force, racket weight etc.

The following set of hypothesises indicate what phenomena might be explored by studying the effects of varied racket moment of inertia.

i. Higher moment of inertia results in higher power and therefore ball speed.
ii. Lower moment of inertia results in better racket mobility and, therefore, control.
iii. Higher moment of inertia results in more racket stability and, therefore, less discomfort and vibration when hitting off centre.

6.3 Participants

To test these hypotheses, a suitable participant sample group was required. The age range chosen was influenced by the fact that more experienced players are widely accepted to have better proprioception (Brody, 2000) and are also more familiar with the colloquial language associated with the tennis population than less experienced players. Since the test involved some degree of physical activity it was considered ethically sound to use healthy players within the age range of 18 to 55 years old. Both male and female participants were recruited since the test primarily investigated the relationship between player perception and physical measures, thus the physiological differences between male and female players was not likely to have an effect that might obscure the results. Further analysis of the results could help to affirm whether any gender differences existed. Table 6.2 shows a detailed break down of the sample used for this testing.

Table 6.2 Participant sample group details

Player Experience		**Beginner**	**Club Level**	**High Club level**	**County/ National**
Male	14	1	1	10	4
Female	6	0	1	1	2
18-24 years	11	0	1	5	6
25-29 years	4	0	1	3	0
30-34 years	0	0	0	0	0
35-39 years	2	0	0	2	0
40-44 years	1	0	0	1	0
45-49 years	1	1	0	0	0
Total	20	1	2	11	6

Modal Average Age = 18-24 years

6.3.1 Equipment and Test Configuration

Racket

A single light weight Head LM8 racket frame was strung to 57 pounds and adapted to accommodate the wireless data acquisition hardware by hollowing out the grip which allowed space for instrumentation and mounts. Strips of lead weight were fashioned to wrap neatly around the racket frame at predetermined positions which could quickly and easily be moved to change the moment of inertia of the racket within the market range between sets. Four of these predetermined positions lay on the throat and kept racket inertia within the market range, the fifth position was at the tip of the racket head to create an extreme inertia a little outside the market range. Table 6.3

lists the moments of inertia achieved by positioning lead tape at the 5 predetermined positions on the frame shown in figure 6.1.

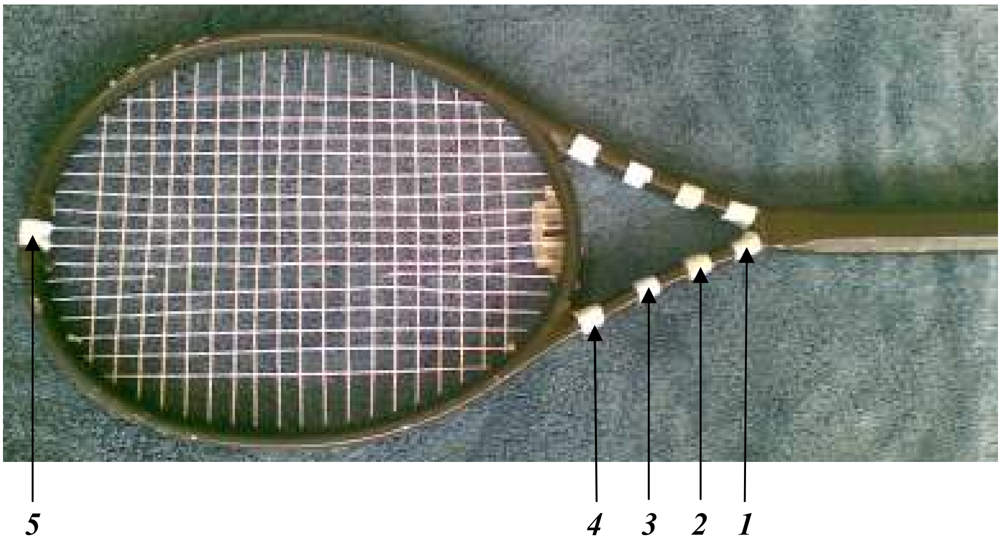


Figure 6.1 The 5 predetermined locations in which to position lead tape to adjust the racket's moment of inertia

Table 6.3 Lead tape positions and associated moments of inertia

Position	Moment of Inertia	% Difference	Classification
1	400	0%	Within market range
2	406	1.5%	
3	412	3.0%	
4	419	4.5%	
5	562	40.5%	Extreme

The changes in moment of inertia were restricted to the start weight of the racket and the market range. Brody (2000) showed that a sample of experienced tennis players were general able to detect a 2.5% change, much more sensitive than that suggested by Webber's law (Fechner, 1860), and the results showed that some might even be able to detect changes close to 1.5%. Further, Mitchell et al. (2000a) and Kotze et al. (2000) demonstrated a ~10% change in moment of inertia spread across a range of 4 rackets resulted in consistent correlated variation in measured service speed of the same magnitude. Based on this information the moments of inertia tested within the market range (i.e. the first four configurations) were spread across a 4.5% range with around a 1.5% change between each racket, thus the participant could be exposed to a change in the range of 1.5 to 4.5% dependent on the racket order.

Although well respected researchers in the field give good reason to believe variations within the market range are readily detectable Kreifeldt and Chuang (1979) report that Webber's law does not hold when moment of inertia is considered, suggesting that people are far less sensitive, with players only able to distinguish between rackets with at least 25% difference. The fifth inertia value outside the market range, 40.5% above the lowest value, was included to provoke this response in the absence of more subtle findings.

The added lead weight mass was the same in all the positions, which ensured that the total racket weight was consistent throughout the test. To maintain a consistent balance point would require careful and precise distribution of the lead weight, which was very difficult to achieve given the shape of a tennis racket and potentially very time consuming making it impractical to change between test sets. In the market range, the majority of rackets with a higher inertia will also have a higher balance point, and as such could be considered to be closely related, and in this case will have to be considered as a single phenomenon.

The BTI wireless data acquisition hardware, described in Chapter 5, was inserted into the butt of the hollowed out racket handle, with Flexiforce sensors and three uni-axial accelerometers mounted as shown in figure 6.2.

Figure 6.2 Wireless instrumentation system mount open displaying arrangement of FlexiForce sensors, accelerometers, wiring and data logger

A Lobster ball machine was used in the test to feed balls to the player. The single, relatively low speed of the ball machine lent itself to a shot that might be played when an opponent 'breaks the angle'. 'Breaking the angle' refers to a shot that is played straight in reply to a crosscourt building shot, and generally used if the player has a good attacking opportunity as an approach shot to the net. To mimic this type of shot the feed from the ball machine was straight down the line to the player's forehand. The crosscourt forehand shot was selected as the shot to be played by the participant because it is a commonly used rally ground stroke and, owing to the maximum length of court being available, is hit with more power than the bulk of other ground strokes.

Ideally the ball cannon feed would maintain a constant line and depth, in practice the ball feed varied over a 0.75 metre range, and a 0.25 metre width range. The variability in ball feed could have an affect on the repeatability of the players' shots, however, it was deemed to be acceptable relative to the much higher variability that occurs in real play. This was reviewed and confirmed in the pilot test by questioning the participant post test. To achieve better consistency of feed a new ball machine would have to have been sourced which was not logistically possible, and unlikely to significantly improve the quality of the data.

6.3.2 Ball Trajectory Control

A 'SpeedCheck' radar similar to that used by Bowyer (2003) was set up at the centre of the court facing away from the player such that they were unable to see the readout. The 'SpeedCheck' radar uses the Doppler shift in the detected waves from the transmitted waves to calculate a moving objects velocity. The ball speed measures were tested for repeatability using the Lobster ball machine feed as a reference.

Crosscourt from the player a grid was marked out with tape. One of the squares was marked as a target for the player to aim for. The grid square chosen as the target square is depicted in figure 6.3.

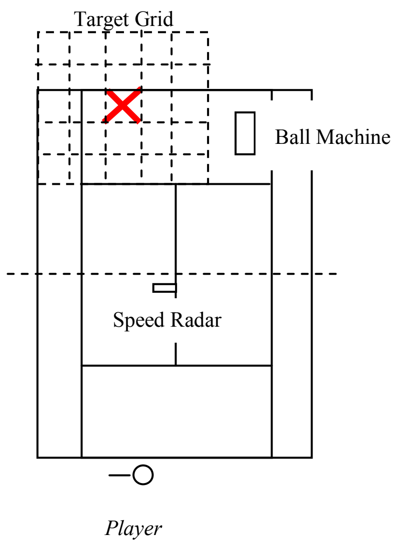


Figure 6.3 Crosscourt target area

The target square selection was based on consultation with a number of players and coaches who were in some agreement that rally shots should be directed cross court as deep as possible but a safe distance from the side lines. Some coaches advised that players should aim to hit somewhat shorter balls to ensure consistency. In the literature Brody (1993) refers to players playing the majority of ground strokes within 8 feet of the base line. Stanbridge (2003) used the baseline to assess accuracy with a system that scored shots closest to the baseline highest and those furthest away lowest. McCarthy (1997) used target squares 1.5 m by 1.5 m that were positioned just inside the baseline on either side of the court, effectively asking the players to attempt to hit with 1.5m of the baseline. The grid square closer to the baseline was selected as the target square to motivate the participants to achieve more demanding accurate shots and to maintain consistency with accuracy assessment described in the literature.

6.3.3 Test Questionnaire

To elicit specific player perceptions a questionnaire was developed from the 'feel map'. The questionnaire was designed to use vocabulary that would be familiar to experienced tennis players and reduce any chance of misinterpretation of the questions. A linear analogue scale was used for the player to rate their perceptions assessment with labels to indicate positive negative and neutral points along the line as shown in the figure 6.4.

How did the racket sound?

High pitch — low pitched

ping
ting
tinny

dull
dead
thud

Figure 6.4 Sample test questionnaire question

Several alternative methods of rating player perceptions were considered before finally deciding that a linear scale would be most beneficial. As discussed in Chapter 4 (section 4.3.4), Blair (2003) reports that the MIT, USA, Sports Innovation Centre's research experience suggests that the majority of human beings cannot consistently discriminate preference on a scale finer than five points. Roberts (2002) and Davies (2003) used a nine point scale since it is commonly accepted that participants will often avoid using the extremes of a scale, and with a large number of comparisons to be made a five point scale was too coarse to identify a difference between the rackets beyond a pair-wise comparison. Since the sample group was not large in this case, and since it allowed more flexibility in the data analysis and normalization, the linear scale seemed to lend itself to this application. Guilford (1984) suggested that the linear scale could also be an effective tool in establishing statistical significance in a sample. The complete questionnaire is shown in Appendix 5.

6.3.4 Additional Controls

The balls used for testing were also a potential source of variability in the test. To keep this factor as consistent as possible new balls were opened for the start of every test. Every ball was run through the ball cannon to the participant, and any balls the player felt were not up to standard, or noticeably different from the rest in any way, were removed.

Other extrinsic variables to be considered included environmental factors, such as temperature and humidity. Temperature and humidity can affect the physical properties of a tennis ball, the racket and the court, and can also affect human physiology. To have some control over these environmental factors testing was conducted on indoor tennis courts that were not vulnerable to the full extremes of the outdoor conditions.

6.4 Perception Test Protocol

An overview of the test protocol is shown in table 6.4

Table 6.4 Test Protocol

<table>
<tr><td>Participant filled out information sheets and consent forms</td><td>5 minutes</td></tr>
<tr><td>Warm up and familiarise with control racket</td><td>5 minutes</td></tr>
<tr><td>Player instructed to hit 30 forehand crosscourt shots, 15 controlled and 15 powerful, towards the target grid</td><td rowspan="3">45 minutes</td></tr>
<tr><td>Participants asked to fill out test questionnaire</td></tr>
<tr><td>Racket moment of inertia adjusted by relocating lead tape on the frame and test repeated for 4 or 5 different moments of inertia as time allowed</td></tr>
<tr><td>Players asked for feedback on the interview process and thanked for their participation</td><td>5 minutes</td></tr>
<tr><td>Total time</td><td>1 hour</td></tr>
</table>

The test protocol began by asking the participant to hit a set of crosscourt forehand shots with a control racket, in this case a Head Intellichip racket. This warm up process was done using the ball cannon set up for the test and thus acted to familiarise the player. The control racket a was chosen to be unlike any racket that a high level player would be likely to be accustomed to and to be very dissimilar to all test rackets so as not to biase subsequent readings or subject responses..

After the warm up and familiarization, the player was given the test racket and instructed to hit 30 crosscourt forehands towards the target grid, 15 controlled shots, followed by 15 power shots. In each case the player was asked to try and emulate a shot they might play in a game situation. The participant was instructed to hit the control shots at the target square with as much control as possible, as they might when building a rally in a game situation, and instructed to hit the following power shots at the target square with as much power as possible, as if they might do when going for a winning or high pressure shot in a game situation. The player was then asked to fill out the pre-prepared test questionnaire whilst the racket's moment of inertia was adjusted according to a Latin square ordering in preparation for the next run. The player then repeated the process with, time depending, four or five different moment of inertias. The grid reference for where each shot landed was recorded, with balls that entirely missed the grid denoted with an 'X' and those in the net denoted as an 'N'. The accuracy data gave an indication of how much control the player had with each racket. The speed radar read out was recorded with the accuracy data to gain some insight into how much power the player could generate with each racket. The data from the accelerometers and FlexiForce pressure sensors were fed into and recorded automatically by the wireless data acquisition hardware.

Of the 20 participants tested one data set had to be entirely rejected after the test was terminated midway through the first set when a string broke on the test racket. A further 4 of the tests returned corrupt or incomplete data sets from the wireless data logger; the rest of the data for these participants was complete and able to be used for the subsequent data analysis.

Testing with the remaining participants generally went well with full data sets collected and many players returning positive feedback about the test, most finding it interesting and rewarding. Despite some initial problems with reliability, the equipment appeared to perform satisfactorily and an initial review of the data indicated that it was within the expected range. In many cases all five racket configurations were able to be tested, although some participants only completed four rackets due to time restrictions. This had implications for the results analysis which are discussed in more detail in Chapter 7.

6.5 Summary

Moment of inertia was selected as the most appropriate and relevant racket characteristic to investigate the relationship between objective and subjective measures. Moment of inertia presented itself as a viable variable with anecdotal evidence to suggest it has a considerable influence on performance and feel.

A test racket was configured to accommodate a tri-axial accelerometer, 3 uni-axial accelerometers and 2 FlexiForce pressure sensors in a fashion that minimised its influence on the racket and the player's perceptions and performance. Lead tape was used to alter the moment of inertia of the racket frame within the market range by discretely securing it at 4 predetermined positions. A further fifth 'extreme' location allowed the moment of inertia of the racket to be increased well above the market range.

The perception relationship model was used to prioritise areas of interest and identify vocabulary most familiar to participants to create a test questionnaire. The questionnaire was used to collect player perception data alongside the objective measures taken by the wireless data acquisition system and measures of ball speed and accuracy described in more detail in Chapter 7.

A test protocol was developed to investigate the effect of changes in racket moment of inertia and the relationship between the subjective measure of player perception and objective physical measures. The results of the testing were intended to verify and define interdependency links indicated on the feel map. Testing demonstrated the application of the protocol, generating a considerable wealth of data analysed in more detail in Chapter 7. The perception test format, in this case examining moment of inertia, could be adapted to investigate a range of different racket characteristics.

CHAPTER SEVEN

PERCEPTION STUDY RESULTS ANALYSIS

7.1 Introduction

The many different forms of data collected from the study described in Chapter 6 required a wide range of methods to calculate measures, correlations and statistical relationships. A total of approximately 2750 sets of physical impact data were recorded from 20 participants, each set containing 6 channels of accelerometer data, 2 channels of force data, each channel containing over 1500 data points. Accuracy and ball speed data was captured simultaneously for each of the 2750 shots. The perception data amounted to 8 questions per racket per participant equating to around 720 question responses.

Initial analysis involved regression to find any linear line correlations that existed in the physical data. This gave some indication of which physical measures were interdependent and whether sufficient stimulus existed for the players to be able to note a change in their perceptions.

Regression was again used to examine some of the relationships between perception ratings, and then in comparison to physical measures. More detailed measures of statistical significance were also employed to examine these relationships more closely. Much of the data was normalised and statistical ordering tests were used to refine the data set and establish any ranking correlations that might exist.

Findings arising from the completed results analysis are summarised at the end of the chapter along with recommendations for further work.

7.2 Summary of Raw Data

Figures 7.1, 7.2 and 7.3 are a selection of typical vibration traces from the normal axis of the tri-axial accelerometers for various participants. The distinctive shape of the trace is similar to that reported by Bowyer (2003), Knudsen (1991) and Knudsen and White (1989). The point of impact can be clearly distinguished with a pre-trigger hump that can be attributed to the arm swing. The subsequent vibration exponentially attenuates post impact followed by a number of smaller humps that can be attributed to the swing.

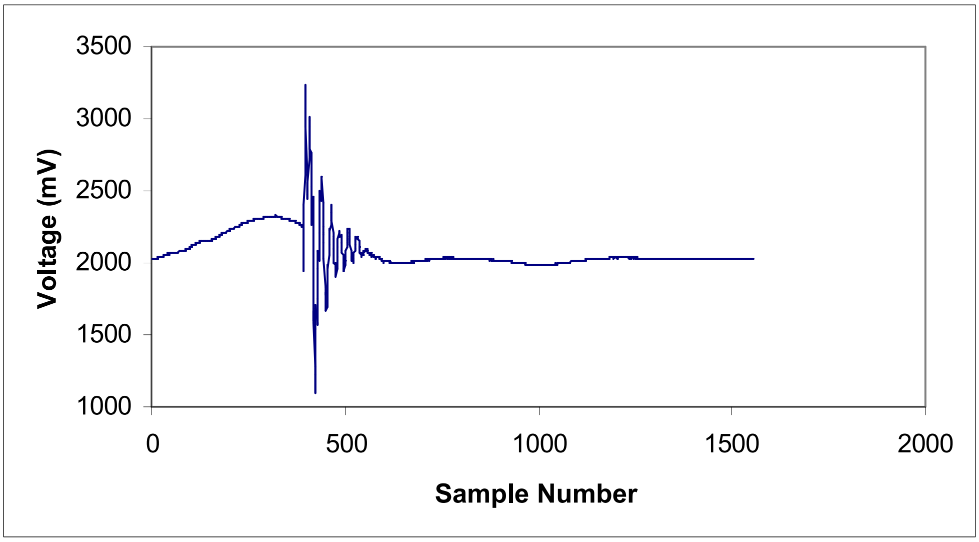


Figure 7.1 An example of a typical normal axis accelerometer trace

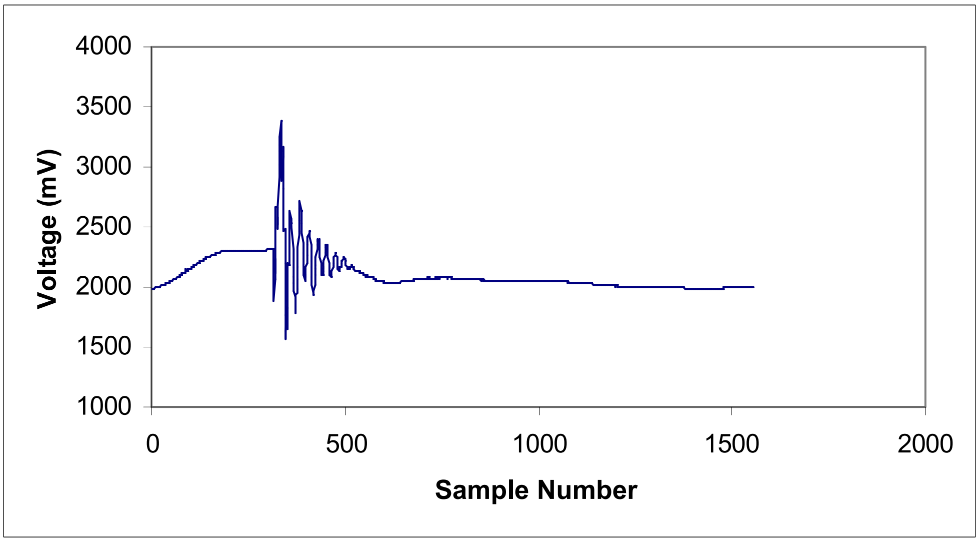


Figure 7.2 an example of a typical normal axis accelerometer trace

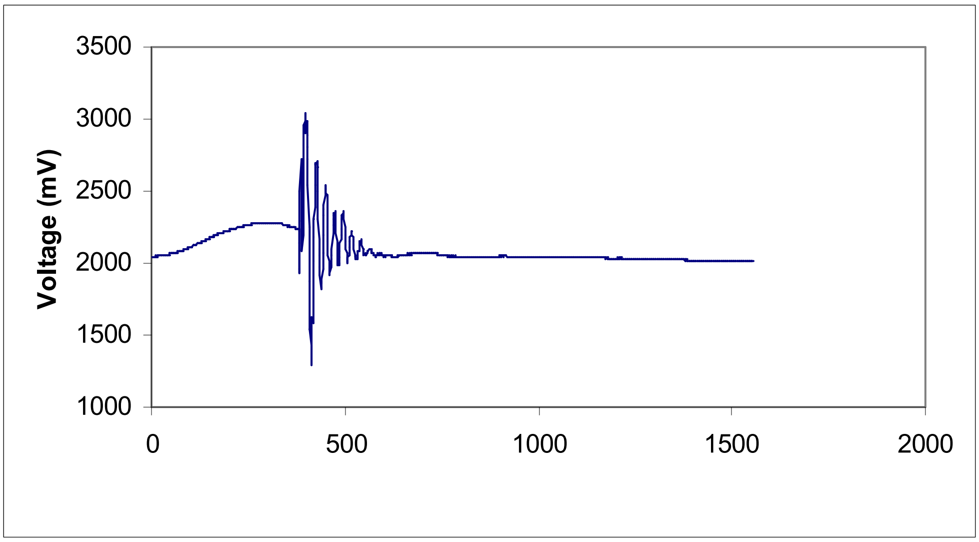


Figure 7.3 An example of a typical normal axis accelerometer trace

In a few cases the participant inadvertently held the racket upside down, resulting in an incorrect trigger and a distinctly different trace as can be observed in figure 7.4. In other cases where the device has been falsely triggered, perhaps by hitting the floor with the racket, traces similar to figure 7.4 were observed, where small multiple shocks were evident with little or no low frequency pre and post trigger humps.

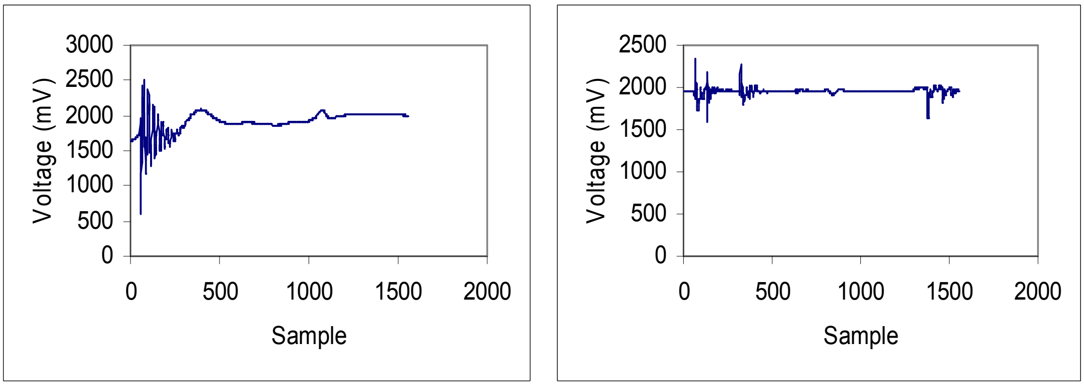


Figure 7.4 Examples of falsely triggered captures

Each participant hit, on average, 144 balls throughout the period of the test, but it was not uncommon to see upwards of 250 captures on the wireless device. The many false triggers needed to be filtered out of the raw data to leave the true impact data for analysis. A Microsoft Excel macro was written in Visual Basic to allow captured data blocks to be quickly and easily browsed. As each block was viewed, a separate macro was used to save desired data to individual excel files, leaving the rest of the blocks to be discarded.

When all the data had been reviewed and the relevant blocks saved, another macro was written to automate the processing of all the data from the individual Excel files and to compile it into a single spreadsheet. The single Excel spreadsheet could then be filtered with the use of the database and array functions to examine specific data in more detail.

Participants were asked to mark their perception ratings on a linear analogue scale similar to that used by Stroede et al. (1998). These analogue scales had to be measured and recorded in numerical form before much of the analysis could be conducted.

The relatively high levels of variation present in this data suggest that participants were stimulated sufficiently to believe they could detect relatively large differences in the qualities of each racket. Figure 7.5 shows a selection of typical perception data with participants exhibiting a high level of variance in their use of the rating scale, each producing a distinctly individual racket perception ‘finger print’.

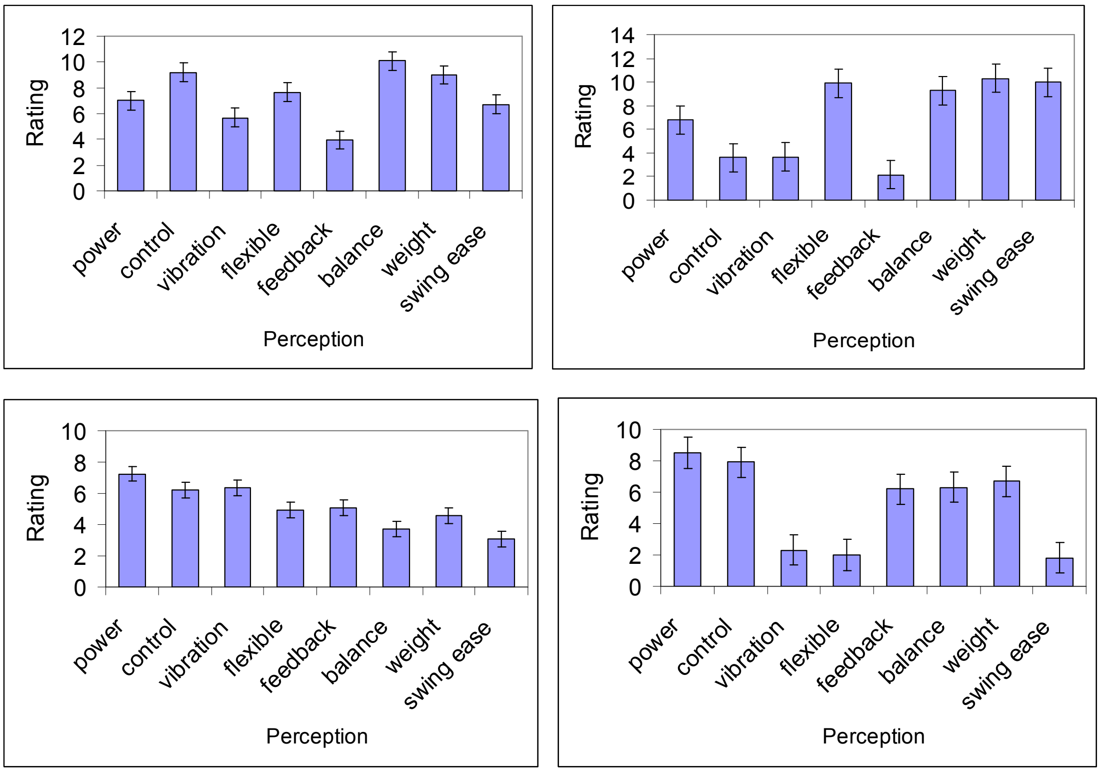


Figure 7.5 Graphs demonstrating the diversity of the perception data

Examining the data in more detail reveals that the participant's use of the rating scale varied between individuals, with some utilising the full scale, some restricted to one end or the other and others avoiding using the extremes of the scale. Figure 7.6 shows how:

- Particpant (a) appears to have not to have been stimulated sufficiently and has selected almost all neutral values
- Participants (b) seems to avoid using the extremes of the scale
- Participant (c) has a tendency to use the upper end of the scale
- Participants (d) and (e) seem to be comfortable using the full extremes of the scale
- Participant (e) has a tendency to use the lower end of the scale

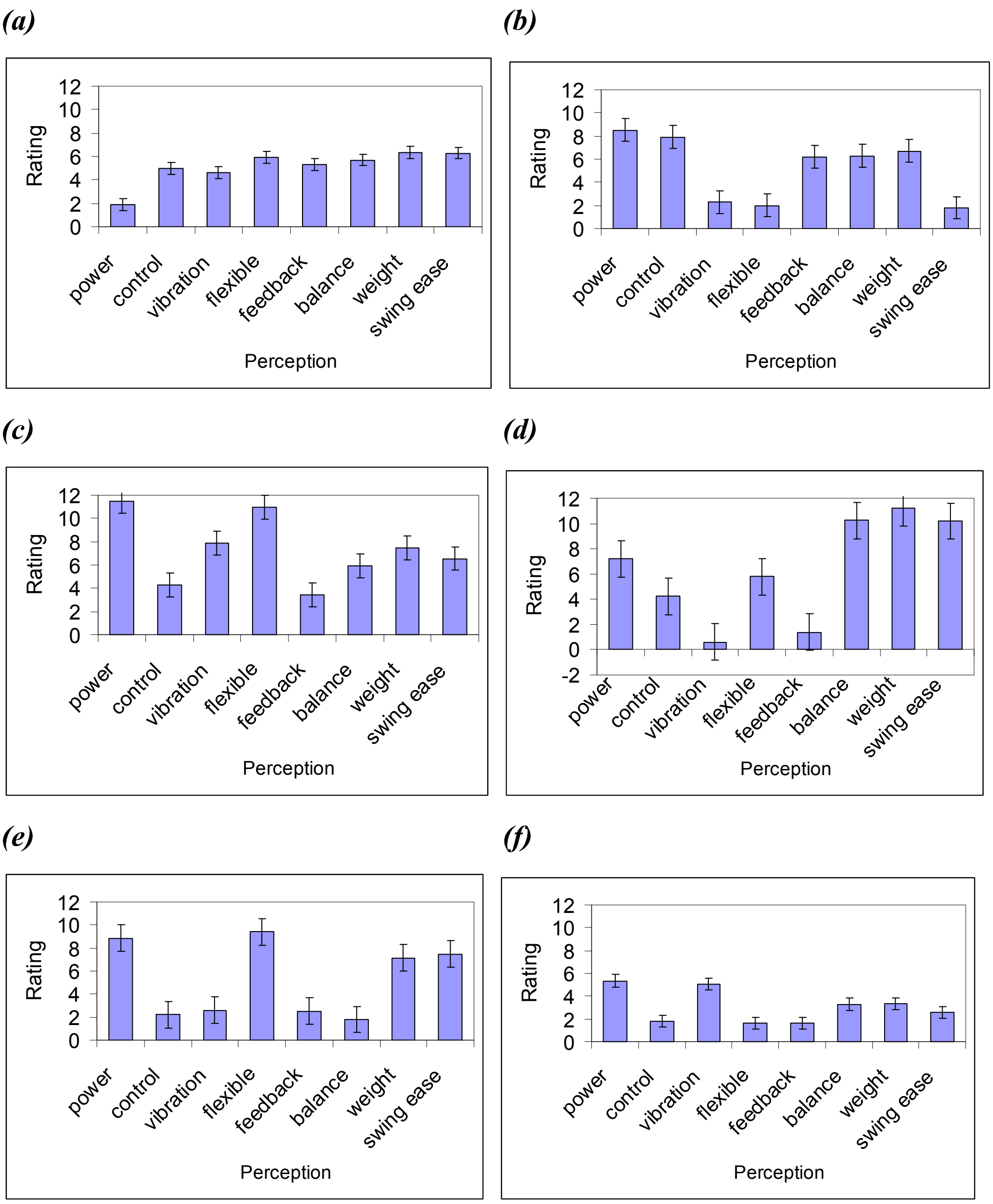


Figure 7.6 Graphs demonstrating the varied use of the perception rating scale

7.2.1 Wireless data logger processing method

The wireless data logger data is downloaded as un-calibrated raw voltage data. This voltage data needed to be converted to more relevant units by using a calibration equation derived from the calibration curve calculated as explained in Chapter 5 (Section 5.6.4). Due to the nature of the data it was not possible to directly average and compare traces without distorting the result. To overcome this problem the data traces were characterised so that comparable numerical measures could be taken from each data set. These values could be averaged and compared through out the sample group. The data traces were characterised as follows:

- The maximum and minimum values in the pre-impact and post-impact phases of the trace were returned so a peak to peak value could be calculated for both. The peak to peak range is a good representative measure of the shock forces experienced by the racket. The shock of impact has been associated with lateral epicondylitis (Cooke et al. 2002, Nallakatla et al. 1995) and as such likely to be an important element of 'feel' (figure 7.7).
- The time taken for the vibration signal to decay was calculated from the post-impact peak to a threshold level. (figure 7.7). The time taken for vibration to attenuate is also associated with lateral epicondylitis (Carroll, 1981) as well as being a tested element of feel in this study.

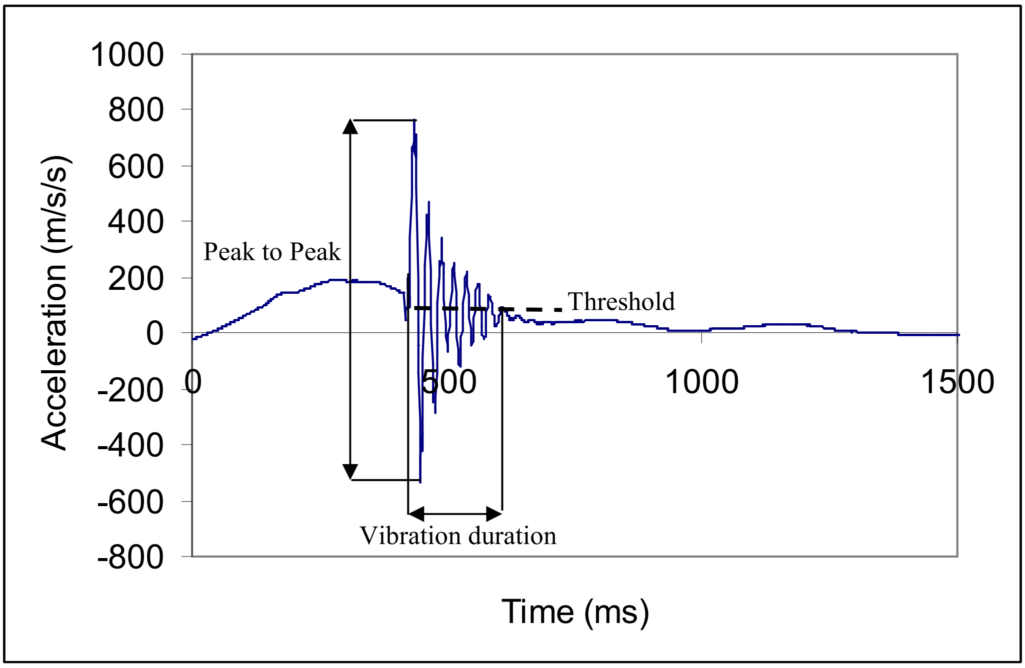


Figure 7.7 Example of typical impact trace

Comparing a series of typical calibrated impact traces it is possible to see the similarities in the peak to peak range and vibration duration values that are reported in the literature. Figure 7.8 shows a typical selection of tri-axial normal axis accelerometer traces taken from several participants.

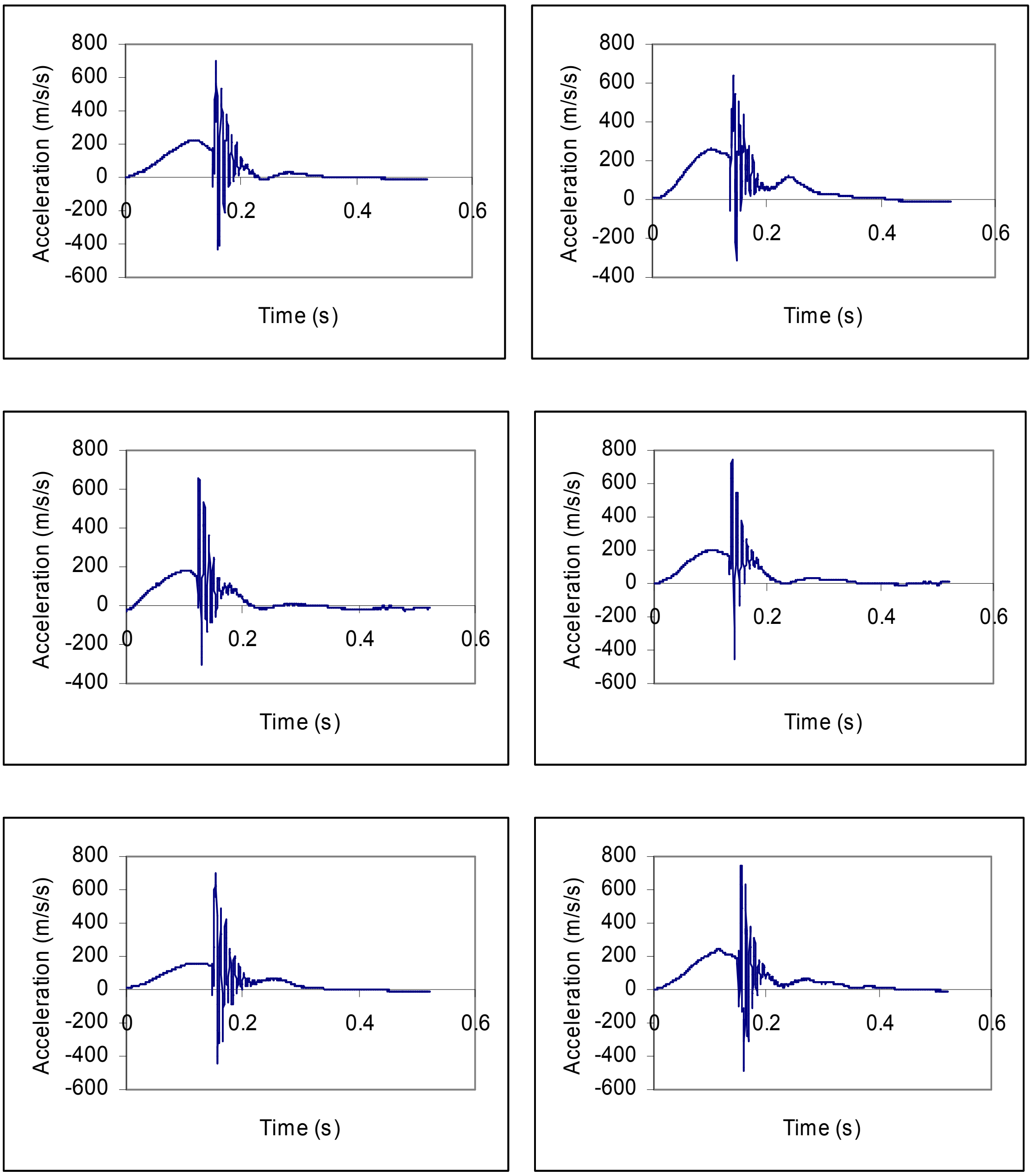


Figure 7.8 Accelerometer data traces comparable to the literature

The peak to peak acceleration values observed in these traces tended to be in the region of 1100 ms^{-2} which is comparable to that reported by Knudsen (1988, 1991) and Bowyer (2003). Similarly the time for the vibration to decay is reported as being in the region of 40ms, just as shown in the data presented above. The main difference between these traces and the majority of those reported in the literature is the pre and post impact ‘humps’. These are present in this study since the tri-axial accelerometer used was capacitance based rather than piezoelectric and thus more sensitive to low frequency vibration.

The entire signal was multiplied by the windowing function shown graphically in figure 7.9 to reduce any step function and leakage prior to performing a Fourier transform.

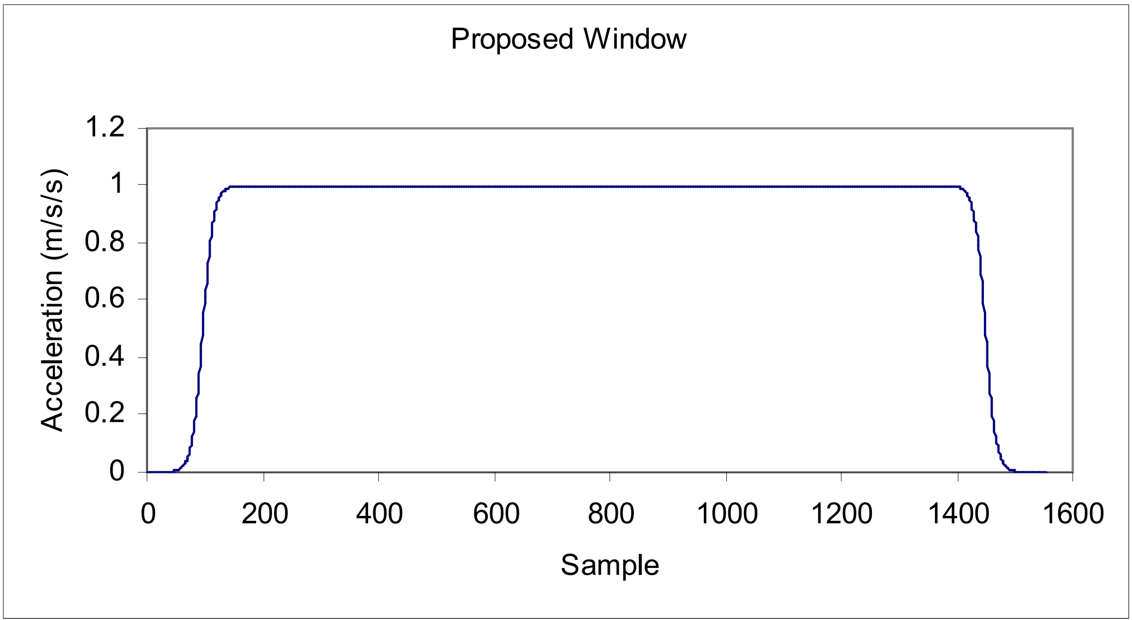


Figure 7.9 Window used to scale accelerometer signal

A number of alternative windows were considered for the task of reducing leakage without compromising the data. The commonly used Hanning window was not appropriate in this case since the signal was not continuous and an unrepresentative emphasis was given to the later, decaying section of the signal. Ellwein et al. (2000) devised a window deemed to be appropriate for impact vibration traces that began with a very abrupt and steep gradient and decayed with a more gently declining S-curve (figure. 7.10).

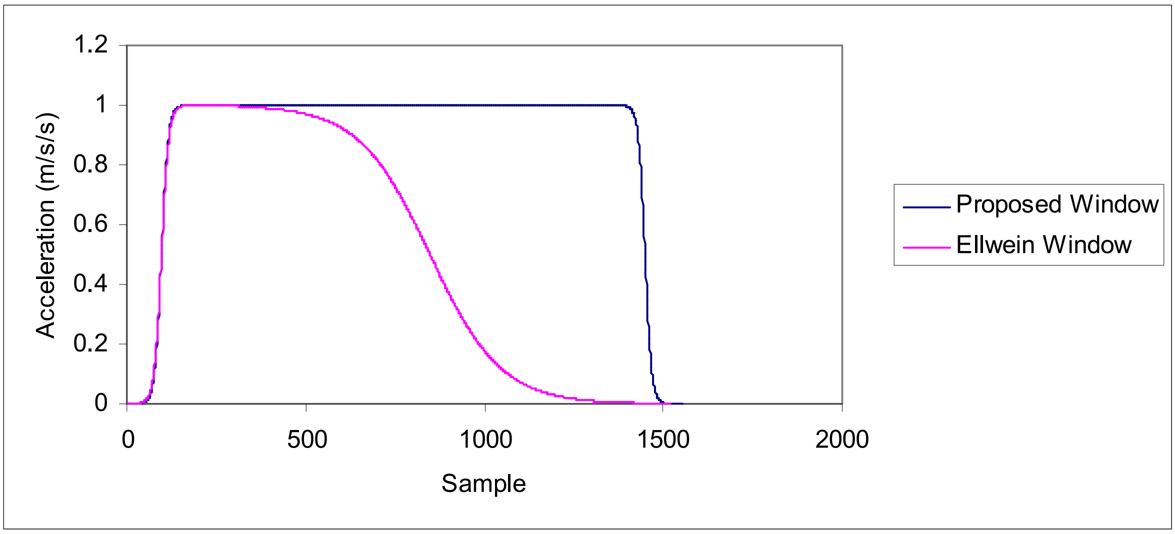
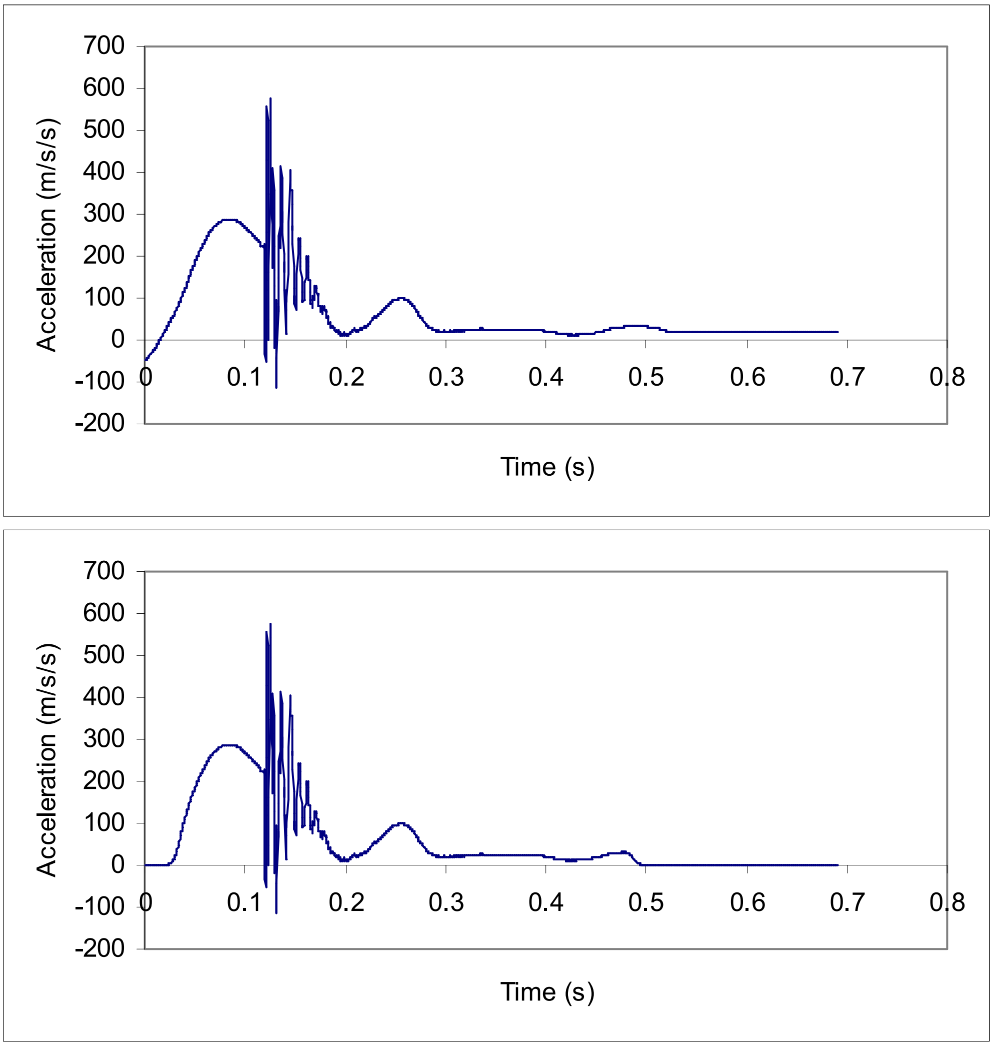


Figure 7.10 A representation of the Ellwein signal window

This window was intended to emphasis the early high amplitude section of an impact signal whilst still reducing the effects of leakage by gradually attenuating the end of the signal to zero. The data collected with the use of the wireless data logger was obviously impact data and of this form. However, the signal very quickly decayed towards zero without the need for a window, so the Ellwein window was deemed to be unnecessary and undesirable since the elongated attenuation would reduce the influence of the later signal amplitudes. To address this the signal window was altered so that the whole signal was given a more even emphasis with a steep but smooth attenuation to ensure the signal was brought to zero where there may be some residual off-set that might be caused by the swing for example. The effects of the windowing can be seen in figure 7.11.

For a fast Fourier transform to be used on the windowed data some amount of zero padding was required so that the number of data points in each signal was a power of 2. In this case this was achieved by repeating the last data point of the captured signal to fill the remainder of the sample.

a)



b)

Figure 7.11 a) Calibrated data trace b) Windowed calibrated data trace

A fast Fourier transform was performed on the windowed data to produce a frequency spectrum similar to the typical selection of various participants' data shown in figure 7.12. The area under the frequency spectrum graph, and the R squared value was calculated, averaged and used as a comparison between rackets and participants.

Figure 7.12 (a) shows how the spectrum was broken into modal sections and RMS values calculated for each individually for comparison. Evidence of leakage, an undesirable side effect of the numerical method rather than true behaviour, can be observed in the sample trace in figure 7.12 (c). This leakage affects the absolute frequency peak, but does not affect the RMS, so comparison can be made of this value irrespective of leakage.

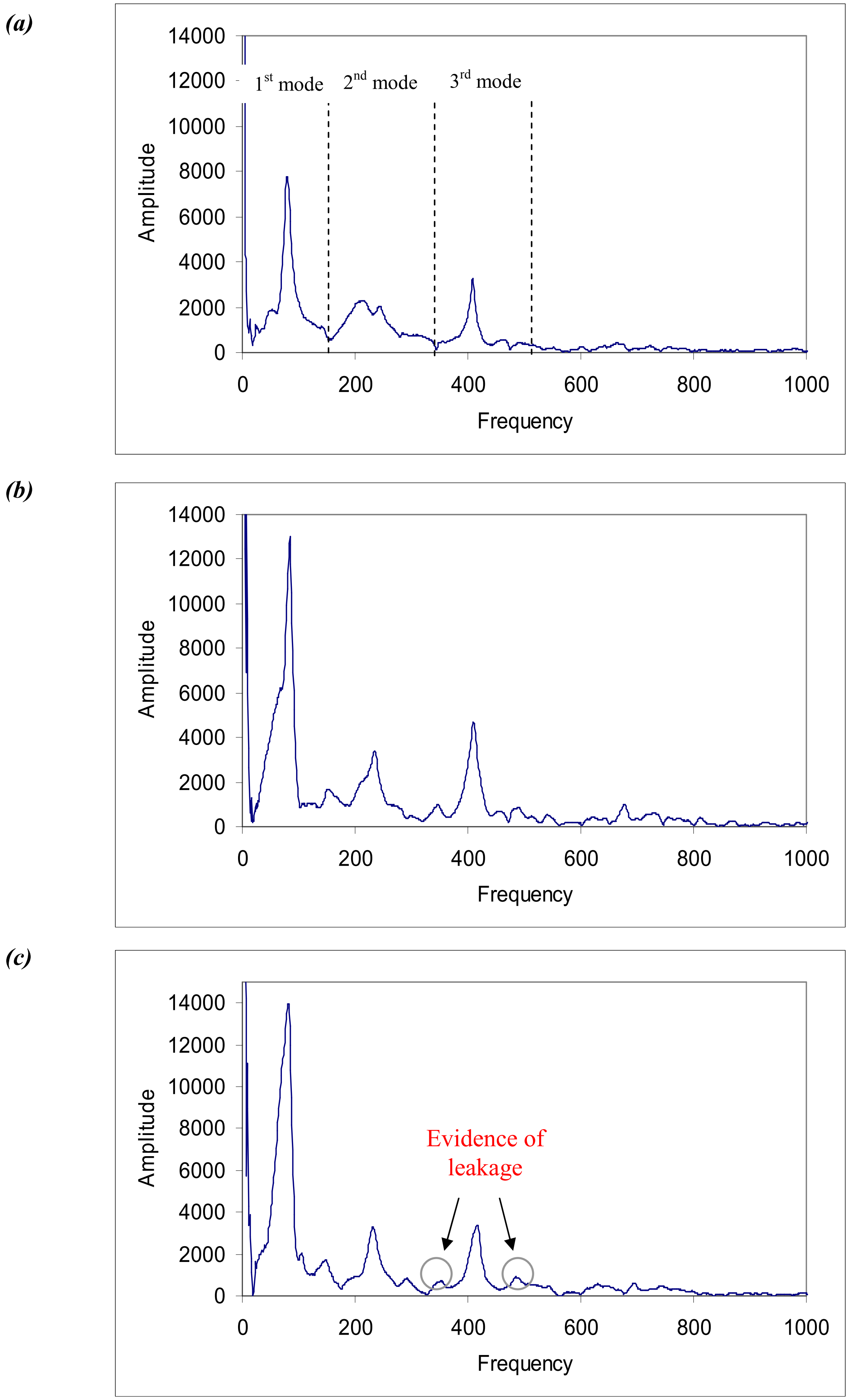


Figure 7.12 Examples of a typical frequency spectrum

7.2.2 Perception data analysis method

The raw subjective perception data was tabulated along with the objective data ready for analysis. A table of correlation coefficients was compiled to highlight any clear linear trends between measures in the data. The stronger correlation coefficients were identified and plotted to visually and statistically assess the relationship between the elements. Best fit trend lines and associated R squared values gave an indication as to how strong any relationship was as shown in figure 7.13.

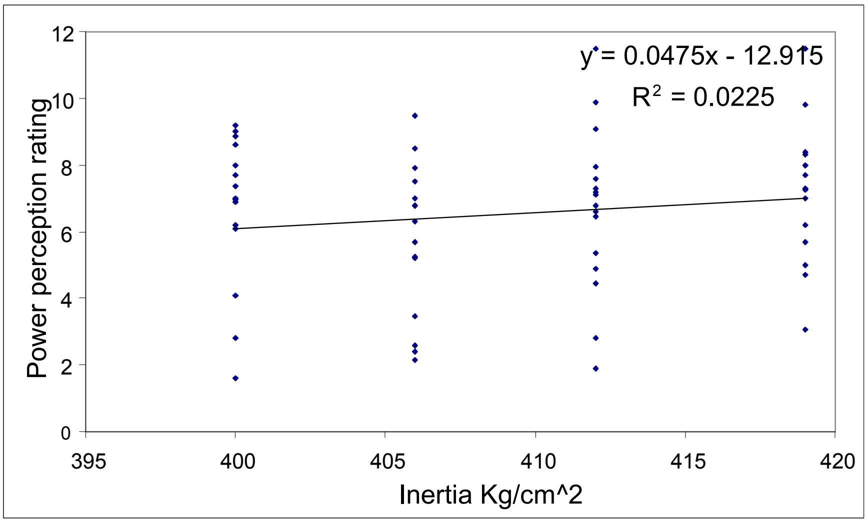


Figure 7.13 Power perception versus moment of inertia and line of best fit

Given the wide spread of the perception data, many of the R squared values were very low, and an alternative statistical test was required to assess the strength of the correlation. A regression analysis was used to calculate the range of the possible gradients of the trend line within the 95 percentile range and an associated P-value as shown in Table 7.1.

Table 7.1 Sample data table for regression analysis

	Coefficients	P-value	Lower 95%	Upper 95%
Intercept	0.46	0.86	-4.60	5.53

The upper and lower percentile levels describe the possible range of the correlation. If both values are positive this indicates that there is a positive correlation, likewise, if both are negative this indicate there is a negative correlation, if one of the values is positive and one is negative, or they lie close to zero then this indicates that no correlation exists. The P-value indicates the probability of this correlation occurring by chance.

With the differences between individuals use of the perception rating scales explained earlier in the chapter, averages of and direct comparisons between the data were not necessarily representative of the experiences of the participants. To overcome this, where five rackets were tested the data could be normalised by calculating the ratio of each response relative to the full response range. An example is shown in Table 7.2.

Table 7.2 Example of one participants normalised perception data

<table>
<tr><th>Racket</th><th>Perception Rating</th><th>Maximum rating</th><th>Minimum Rating</th><th>Full Response Rating Range</th><th>Normalised Perception Rating</th></tr>
<tr><td>1</td><td>6.2</td><td rowspan="4">8.2</td><td rowspan="4">4.9</td><td rowspan="4">3.3</td><td>0.39</td></tr>
<tr><td>2</td><td>5.25</td><td>0.11</td></tr>
<tr><td>3</td><td>4.9</td><td>0</td></tr>
<tr><td>4</td><td>7.3</td><td>0.73</td></tr>
</table>

The normalised data was then analysed in the same way as the raw data, compiling a revised table of correlation coefficients to highlight any clear linear trends that were then plotted for visual and statistical analysis.

It was recognised that some players may be unable to correctly perceive difference and correlation to performance and this may have resulted in low R^2 values. To reduce this effect a method was required to diagnose which participants were more able to perceive these changes. The ability of the participants to correctly rank the racket order was chosen to indicate each individual player's perceptive skill.

A widely accepted statistical methods for assessing rank was utilised; the Spearman ranking test. Initially the numerical values were ordered or ranked and compared to the inertia rankings and Spearman coefficients were returned. A threshold level of 0.6 was set and used to filter out participants less able to perceive differences clearly.

7.2.3 Accuracy and ball speed analysis method

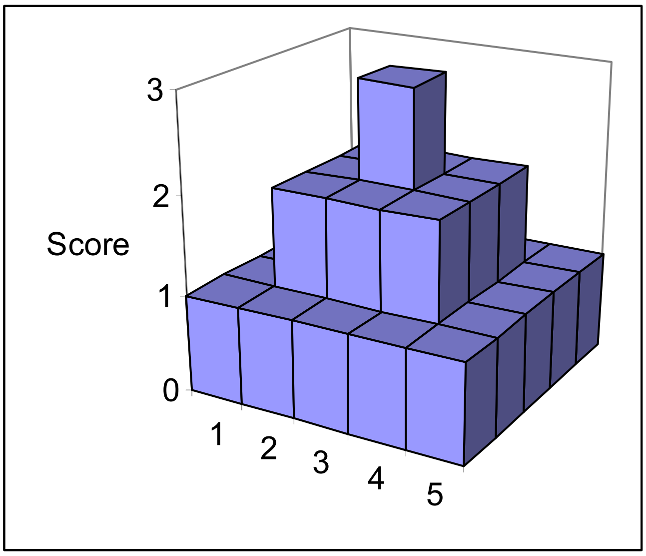
The ball speed collected during testing was in a form that could be used directly in data analysis. It might be argued that one individual may be significantly physically weaker than another, in which case the weaker individual might produce a slow ball speed that they would rate as powerful relative to their even slower normal, rather than in absolute terms. To account for this the speed data was normalised relative to the full range for any individual participant.

The range of the ball speed data was calculated for each individual's data set and each separate measure calculated as a ratio of the total range. This meant that, assuming the players were hitting as powerfully as possible as instructed, physical strength would be compensated for. The weakness of this technique was that players that were able to adapt to reproduce similar ball speeds for each racket type would have artificially amplified differences between sets. Another method of normalising calculated the ball speed as a ratio of the participant's average. Both methods failed to significantly improve any correlations in the data indicating that most players were hitting within a similar speed range, or perhaps equally erratically. There is a clear and significant distinction between the players faster power sets and their slower control sets ($P<<0.01$) which suggests that the players are in fact able to control the ball speed relatively well.

The accuracy data, unlike the ball speed data, was collected as a grid reference and as such was not in a directly useable form. Two methods of converting the grid data to a numerical representation of accuracy were employed and coined the target grid score test and the coach's grid score test:

Target grid score test: This method scored each grid square according to its locality to the target grid in the centre, with more central squares scoring higher as shown in figure 7.14.

1	1	1	1	1
1	2	2	2	1
1	2	**3**	2	1
1	2	2	2	1
1	1	1	1	1



______ = Court line

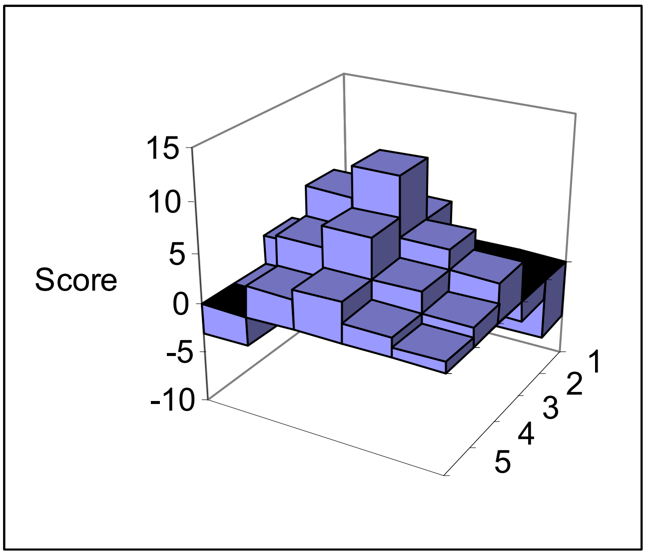
Figure 7.14 Target accuracy score grid

The target grid scoring system method was a logical system similar to those that had been used in a more simplified form (Bowyer 2003, McCarthy 1998). The system assumes that the participant is aiming to hit the target square and that error has equal probability of landing anywhere on the grid i.e. the ball might just as easily land to the left or the right or over or under shoot.

It was recognised that the player's goal may be subtly different to that repeated by the simplistic target grid system and that their perception of performance would be biased so that an existing correlation between perception and performance would not be observed by the primitive bounce score. An alternative was developed to account for this possibility.

Coaches grid score test: This method scored each grid relative to its location on the court. Based on consultation with 3 qualified Loughborough University coaches and comparison with the literature the scores are indicative of the quality of the shot and the associated degree of error in the stroke. Shots that land out of court are scored proportionally lower than shots that land in court, as are shots that are considered to be the result of large performance errors, e.g. shots that are well off line and under hit. Shots that land in very advantageous positions on the court are scored proportionally higher, and those which are near these and in court are scored more reasonably as shown in figure 7.15.

-3	0	-3	-3	-6
0	3	6	0	-2
3	9	**12**	6	4
0	6	8	4	2
-3	3	4	2	1



= Court line

Figure 7.15 Coach's accuracy score grid

The coaches explained that many players would look to aim towards the corner of the court allowing for some margin of error towards both the side edge and the baseline. When attempting to put additional pressure on their opponents the player may aim a little deeper and closer to the lines of the court. The coaches were in agreement that the far extreme of the corner of the court would be a challenging target to hit consistently. The target square was chosen to stretch the players without an unreasonable level of difficulty. Comparisons with the literature show a tendency to rate shots closer to the baseline as more accurate (Stanbridge 2003, McCarthy 1998). The chosen target grid square was in keeping with these publications whilst being considerate of the shots the players would be accustomed to playing in match play.

The two scoring methods were used to convert the grid data to accuracy scores for each set of shots and both were used to investigate any correlations that might exist.

7.2.4 Results analysis

The results analysis begins with an overview of the whole sample examining average trends, highlighting key and unexpected findings in a number of particular objective measures. A more detailed treatment follows, examining each specific racket moment of inertia configuration. Finally the stronger correlations and trends between the subjective and objective data sets are diagnosed and discussed.

Analysis Overview

- **Overview of Perception Ratings**

The differences in the perception ratings of each racket form a unique 'fingerprint' of values that can be seen in figure 7.16.

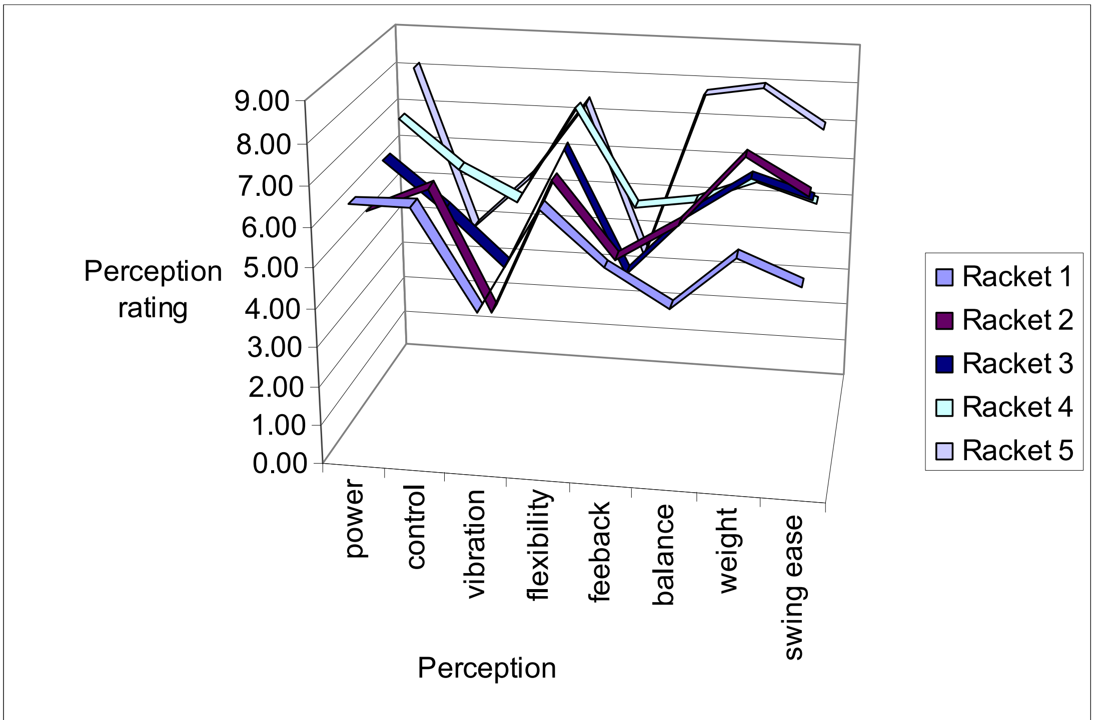


Figure 7.16 Racket perception rating 'fingerprints'

It is clear, that whilst the fingerprint of each racket is unique, the differences are relatively subtle. Figure 7.17 demonstrates the effect of normalising the perception data. The differences between the rackets are exaggerated clarifying each individual racket 'fingerprint'. The average traces shown here are also an indicator of the range of stimulus perceived by the participants. The distinct traces, unlike that which would be expected from random noise, demonstrate a level of general consensus of the sample group.

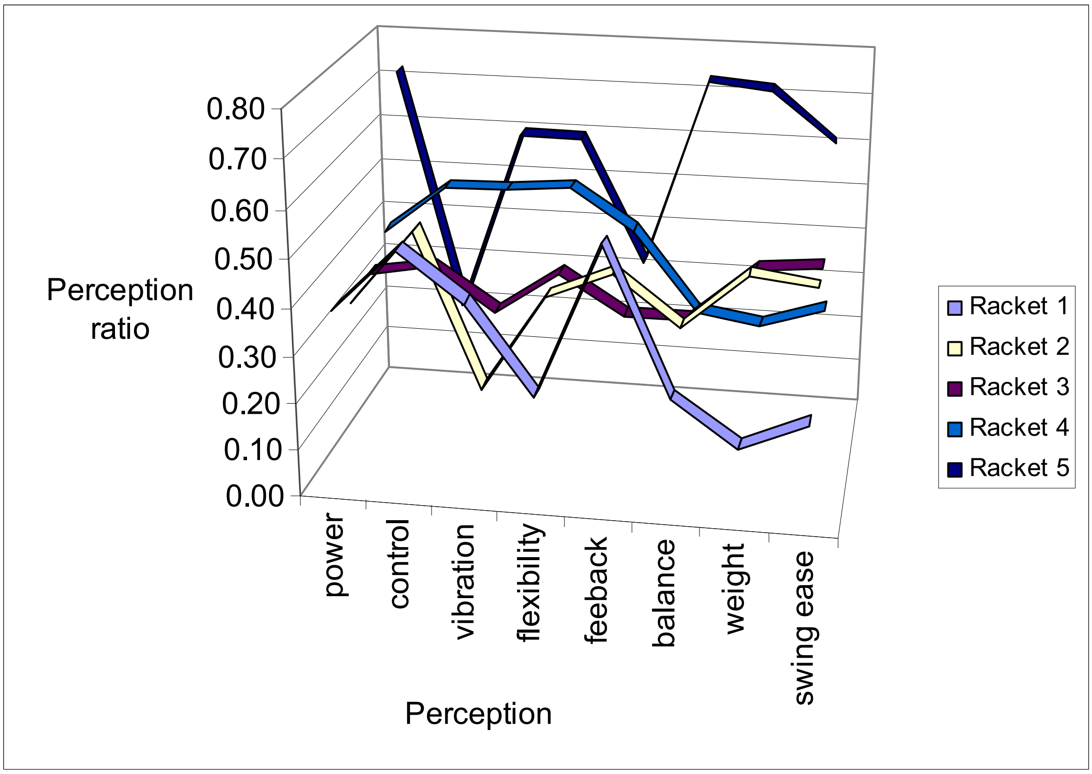


__Figure 7.17 normalised racket perception rating 'fingerprints'__

When the normalised perception data is examined in more detail it is clear that in most cases the maximum average rating for each perception is considerably higher than the minimum, although the standard deviation suggests the spread of data overlaps for all rackets as shown in figure 7.18.

On average participants seemed, as might be expected, to perceive racket five to have the most power, highest weight, balance and lowest swing ease and control and conversely perceived racket one to have the opposite extremes. Racket four appears to have the highest flexibility rating, and there is a general trend indicating that the heavier rackets are perceived to be more flexible. However, the spread of flexibility responses did not vary much between rackets and combined with the standard deviation values make this a less well defined trend.

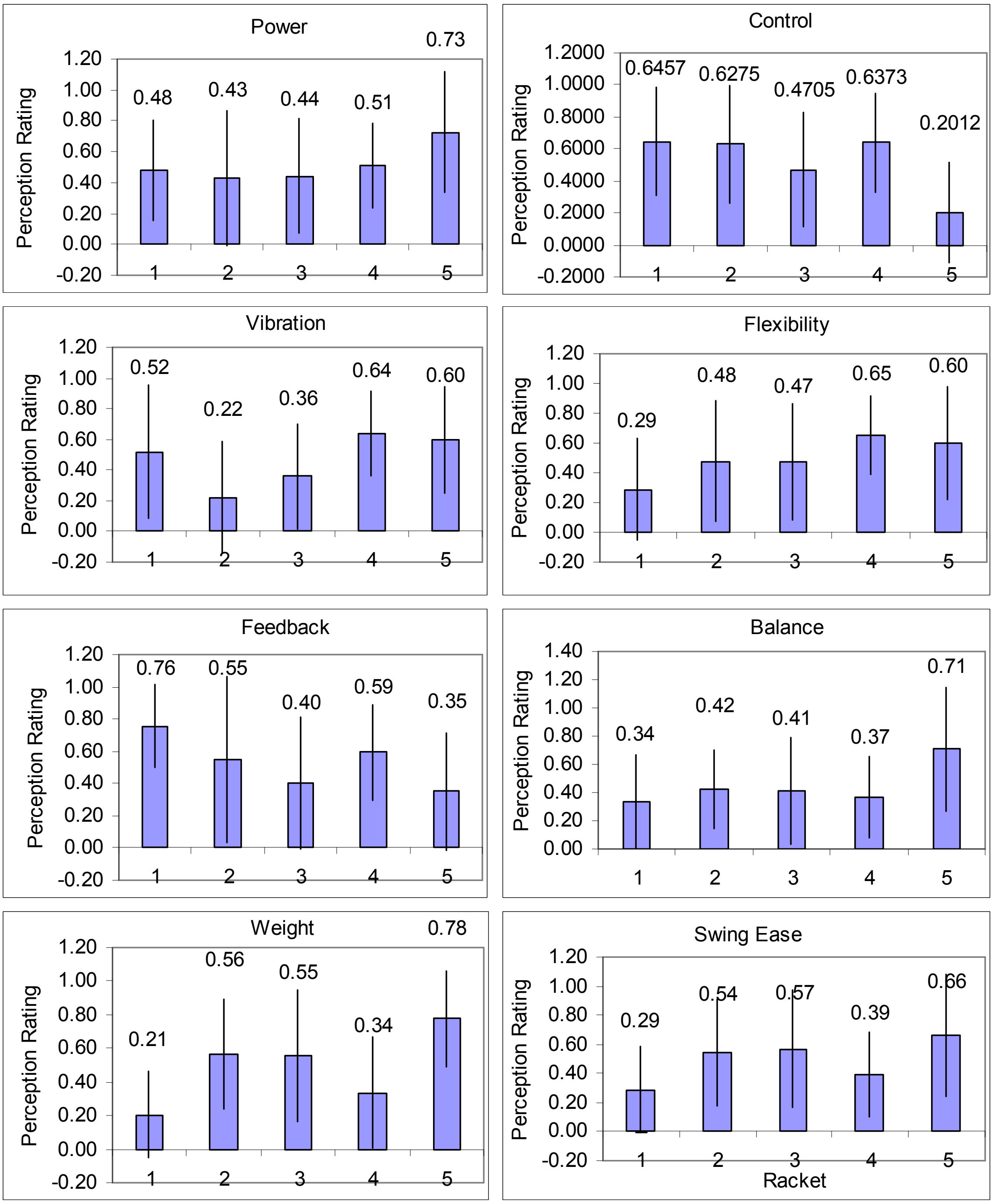


Figure 7.18 Average perception data

Overview of Ball Speed

A summary of the whole sample demonstrates that the players were, as instructed, on average hitting faster balls in the power set when compared to the control sets. Similarly the control sets, on average, have higher accuracy scores than the power sets. The other average data is not so clearly defined across the whole sample; this is not unexpected since the whole group encompasses all the various racket configurations which implies a wide range of data.

Figure 7.19 shows the SpeedCheck average ball speed data plotted against average player power perception ratings. There appears to be a slight positive trend although the data spread is broad and the R^2 value low.

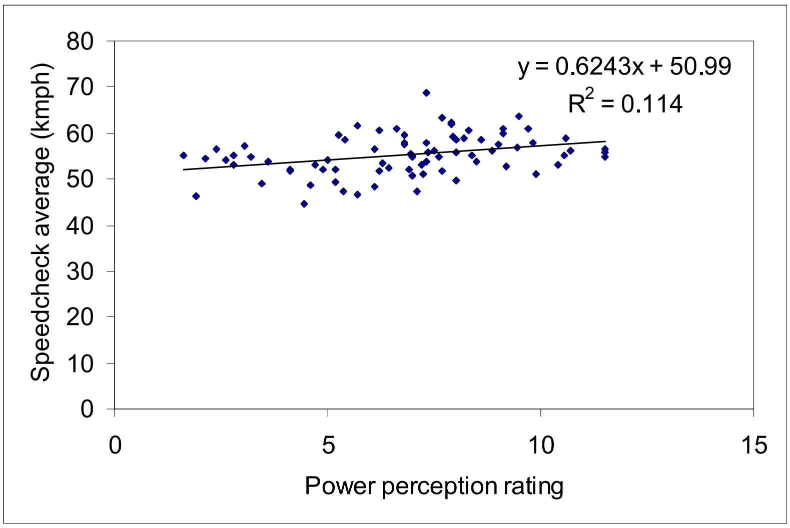


Figure 7.19 Ball speed versus power perception rating

More detailed analysis of specific data sets showed that on average the power sets were hit faster than the control sets. This finding was statistically significant ($P<0.01$) and can be observed in figure 7.20.

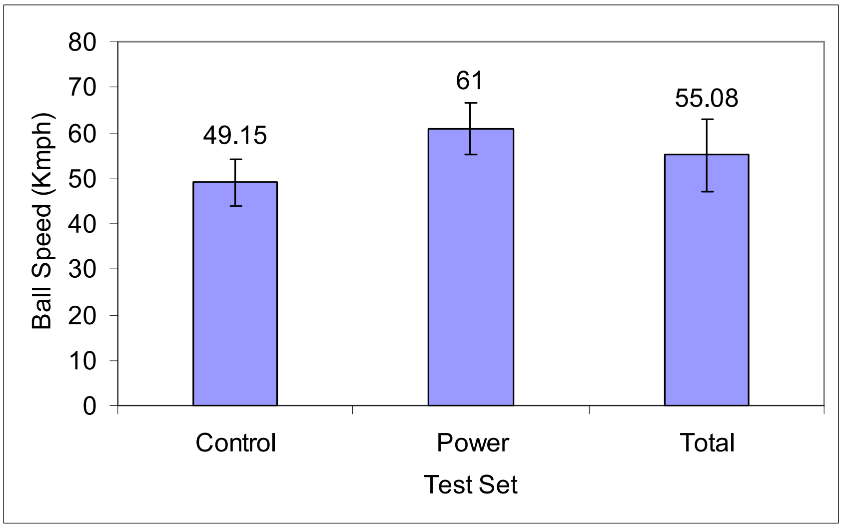


Figure 7.20. Average ball speed data

As discussed earlier in the chapter, it can be argued that the data is misrepresentative since each individual's physical strength is not accounted for. To compensate for this issue both the SpeedCheck and player perception data were normalised as demonstrated in figure 7.21.

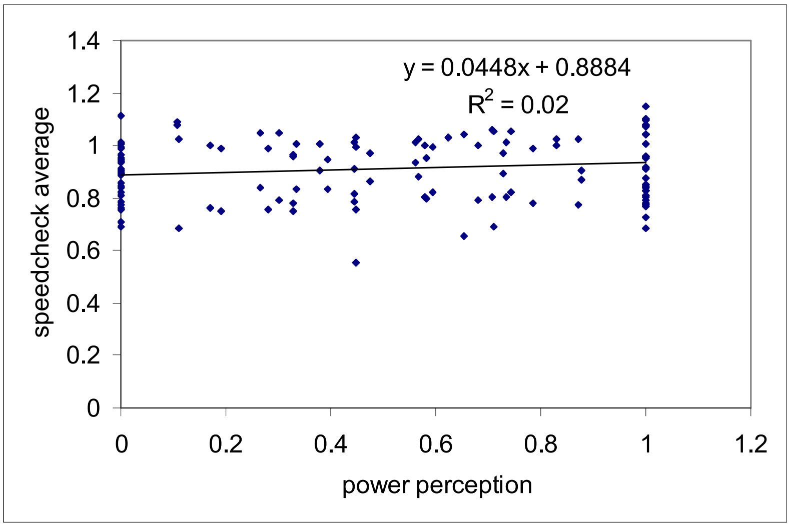


Figure 7.21 Normalised SpeedCheck Data versus Normalised Power Perception Rating

The plot of the normalised data shows that the spread and general trend of the data is not improved. It is interesting that, in spite of the absence of any clear evidence of improved performance, the participants were perceiving some considerable difference in the power of the rackets, suggesting that some other elements aside from the resulting ball speed was influencing their perception of power.

Overview of Accuracy

Figure 7.22 shows how the coach's score system appears to exaggerate the difference between the average accuracy scores for the power and control sets. However, the proportionally higher standard deviation values imply a much wider spread of data with this scoring system. There is a statistically significant ($P<0.01$) difference between the control and power sets for both scoring systems indicating that, as instructed, player were hitting more accurately in the control sets.

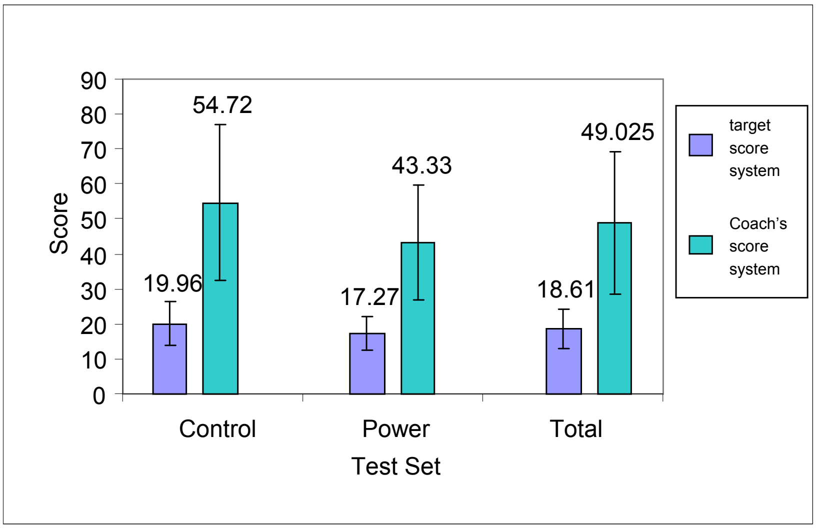


Figure 7.22 Comparison of average accuracy score systems

Given the statistical significance of this observation it is perhaps surprising that there seems to be no obvious correlation between the players' perceived control and the accuracy achieved as demonstrated in figure 7.23. As was the case with power, it seems that players' perception of control is influenced by more than just the resultant accuracy achieved.

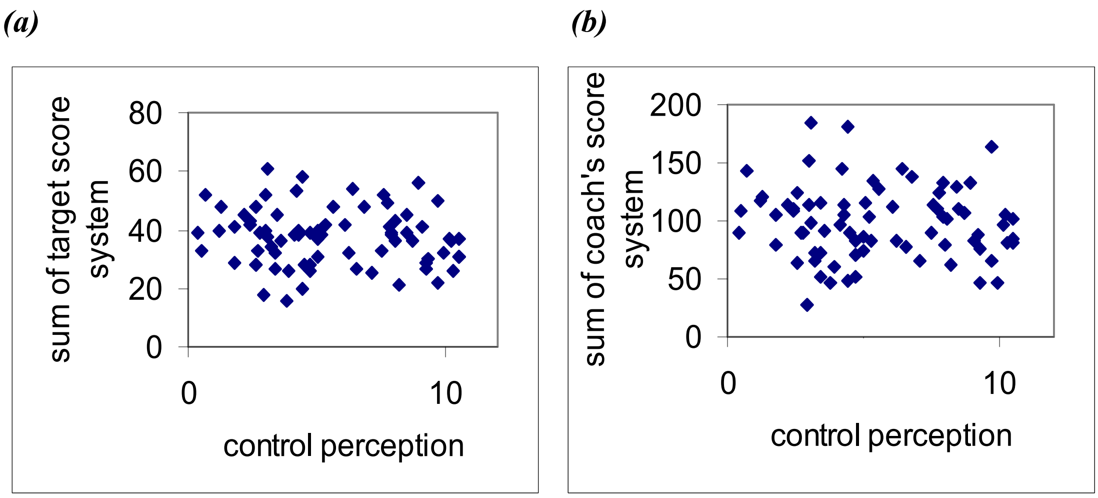


Figure 7.23 Sum of target score system (a) and coach's score system (b) versus control perception

Overview of Vibration

Examining the vibration duration data shows little difference in the averages of the power and control sets. The differences that are evident in figure 7.24 are well within the standard deviation of the data, but do correlate with that which might be expected with longer vibration durations with the power sets compared to the control sets.

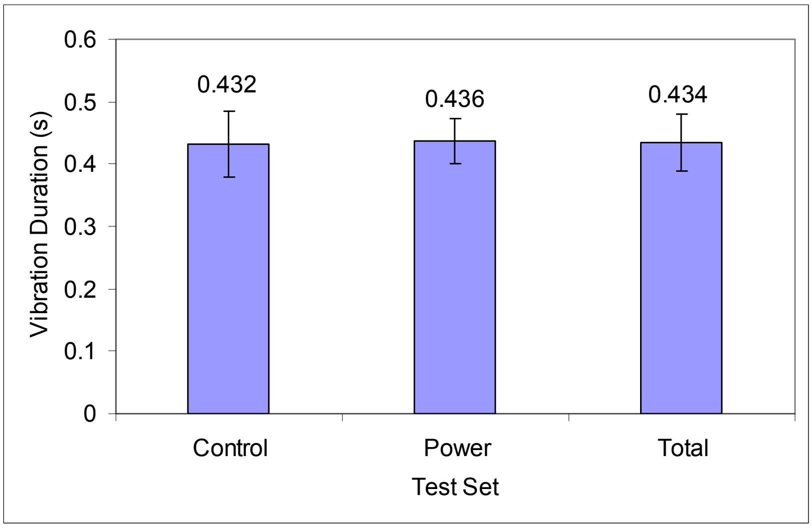


Figure 7.24 Average vibration duration data (tri-axial channel 1)

It is not surprising that, with some level of dampening likely from the mounting configuration, the vibration duration observed in the external uni-axial accelerometers was much shorter than that observed in the tri axial channels as shown in figure 7.25.

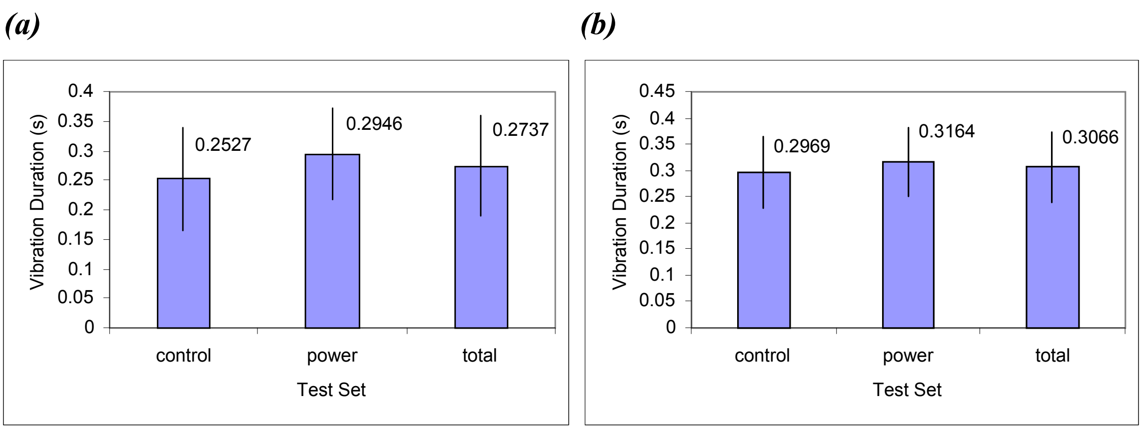


Figure 7.25 Channel 4 (a) and 5 (b) vibration duration

The average vibration durations between the two channels were similar and well within the spread of the data. Again the difference between the power and control sets is within the standard deviation of the data, but there is a general trend for the power sets to have longer vibration durations.

Similarly the average peak to peak acceleration data does not differ vastly between sets, with a large overlap in the standard deviation error bars. However, as figure 7.26 demonstrates, there is a statistically significant ($p<0.01$) trend for the higher peak to peak values to be found in the power data sets when compared to the control data.

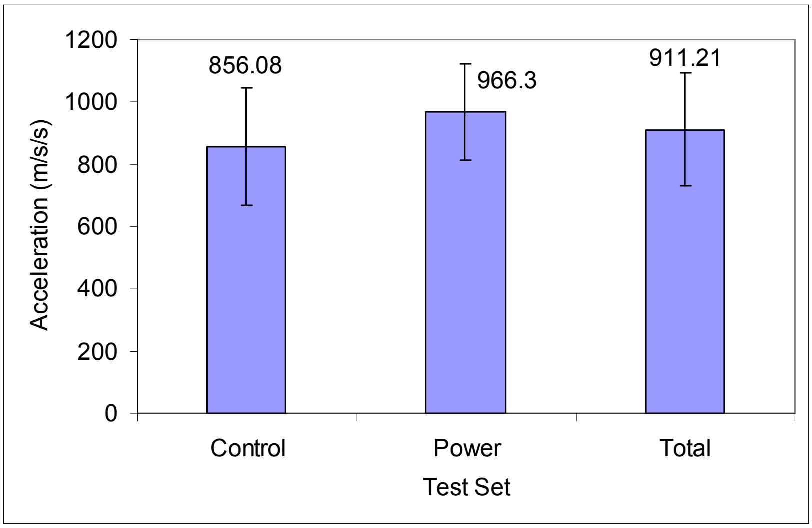
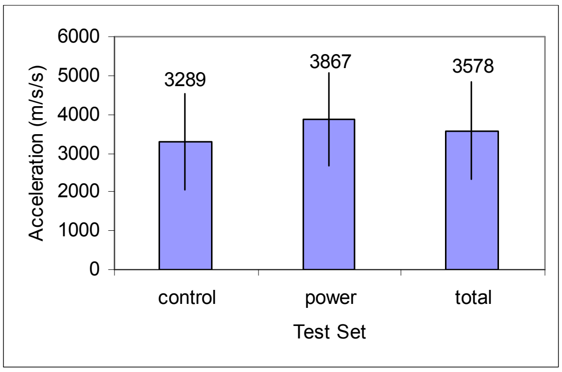


Figure 7.26 Average peak to peak data

With the uni-axial accelerometers mounted some distance from the hand and effective pivot point of the racket, the peak to peak values observed are, understandably, considerably greater than those found in the tri-axial data as shown in figure 7.27.

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



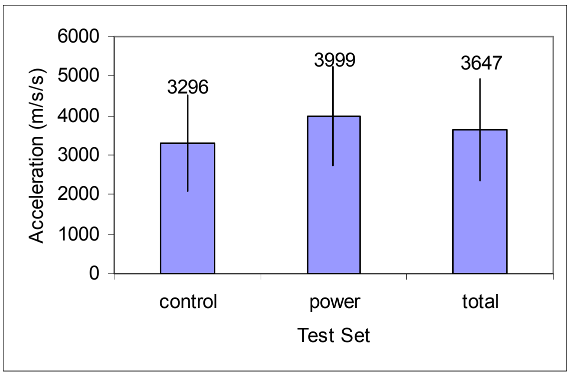


Figure 7.27 Channel 4 (a) and 5 (b) peak to peak

The same trends are evident in channels 4 and 5's data as have been noted previously in many other data sets. The comparison between sets is within the standard deviation of the data but does indicate higher peak to peak values on average for the power sets. The slightly higher values observed in the data from channel 5 might suggest that the players tended to impact the ball towards the top of the racket, although there is little evidence to confirm this with any significance. Similar observation can be made from the subsequently calculated angular acceleration peak to peak values about the longitudinal and transverse axes as shown in figure 7.28.

(a) *(b)*

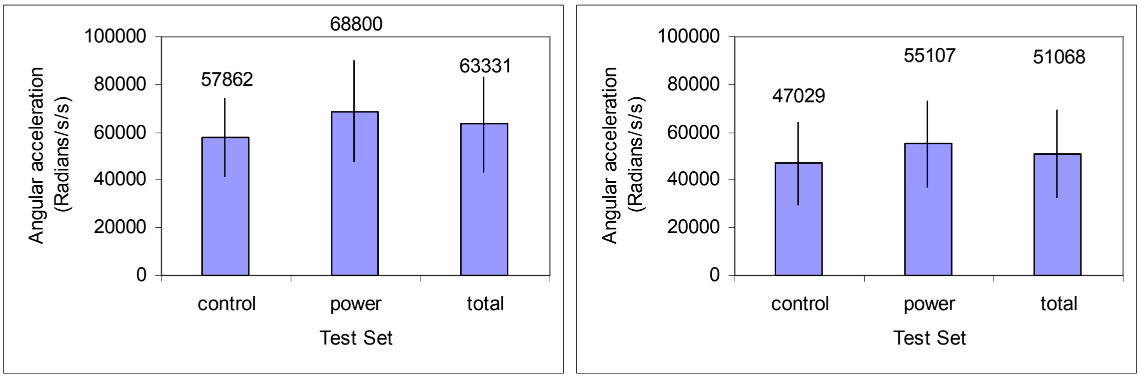


Figure 7.28 Peak to peak angular acceleration values about the longitudinal (a) and transverse axis (b)

Although the data values are all relatively closely matched and certainly of the same order of magnitude, it is apparent that higher angular accelerations are present in the 'twisting' action of the racket in the hand about the longitudinal axis than those about the transverse axis.

Overview of Spectral Analysis

Perhaps of most interest in the average spectral RMS data is the 2nd mode data which is significantly higher in the power set when compared to the control set ($P<0.01$). Although less pronounced the same trend is significant for the 3rd mode ($P<0.01$). Since there is no significant difference in the 1st mode between sets, this finding suggests that it is the higher frequencies that are most effected by performance changes and perhaps these frequencies have a higher influence on racket feel (figure 7.29).

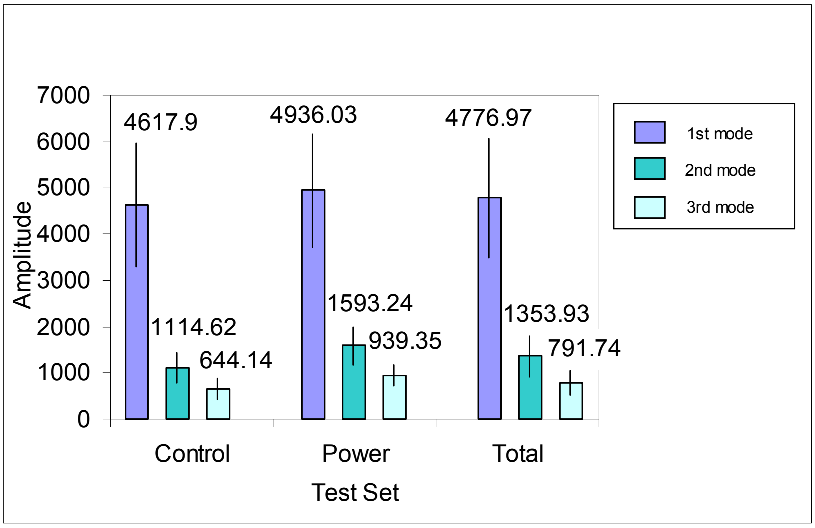


Figure 7.29 Average spectral RMS data

To examine this possible relationship the RMS of the 1st and 2nd modes were plotted against vibration perception. Figure 7.30 shows that although to the casual eye there might appear to be more correlation with the RMS of the 2nd mode and vibration perception, than with the 1st mode, none of the data displays any clear relationship. In fact the relationship that is indicated in figure 7.30 (a) and (b) is contrary to that which would be expected if players were able to detect a difference in the vibration modes i.e. they indicate that they feel less vibration when in fact there is more.

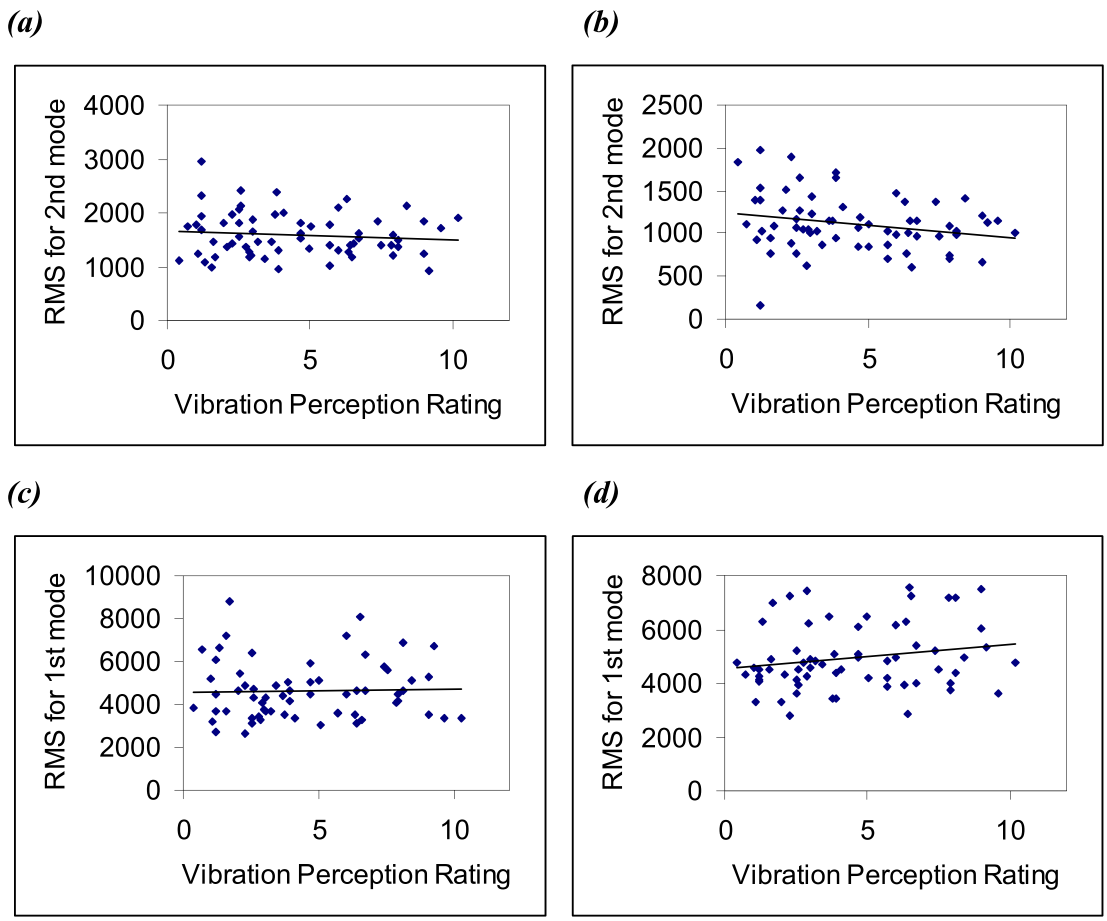


Figure 7.30 RMS for 2nd mode of control set (a) and power set (b) versus vibration perception rating and RMS for 1st mode of control set (c) and power set (d) versus vibration perception rating

Specific Racket Analysis

- **Racket 1**

Examining the average data from racket 1 alone demonstrates the difference between the resultant ball speed from the players' shots from the power and control sets as can be observed in figure 7.31 (a). In the case of this lowest moment of inertia racket configuration it seems that the difference in accuracy is not evident as it was when the sample was considered as a whole as shown in figure 7.31 (b).

a) *b)*

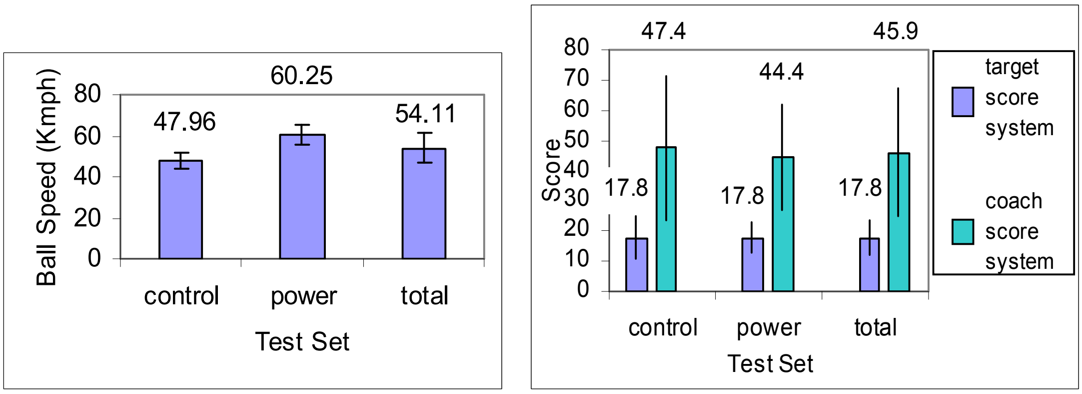


Figure 7.31 Ball speed (a) and accuracy data (b) for racket 1

- **Racket 2**

Although the data for racket 2 still consistently indicates that the power set is being hit harder than the control set, with the second racket accuracy score differences are now also beginning to become more evident as can be observed in figure 7.32 (a). There is also some indication that higher vibration measures are more common in the faster power sets with this racket as shown in figure 7.32 (b)

a) *b)*

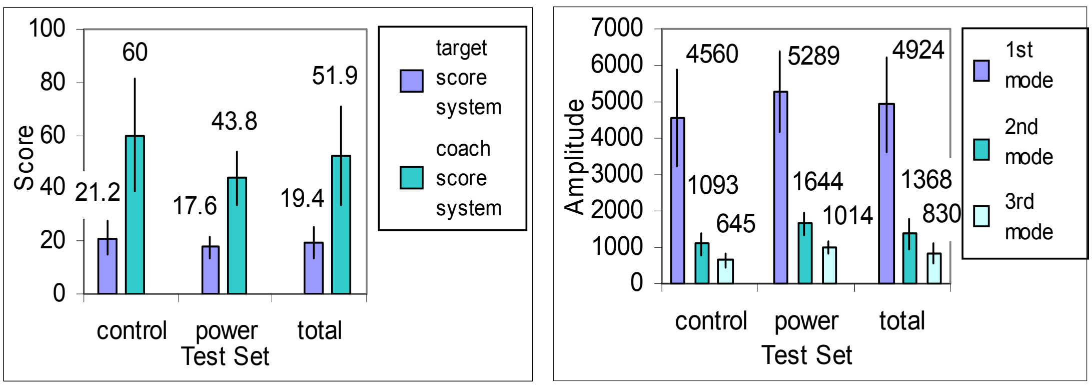
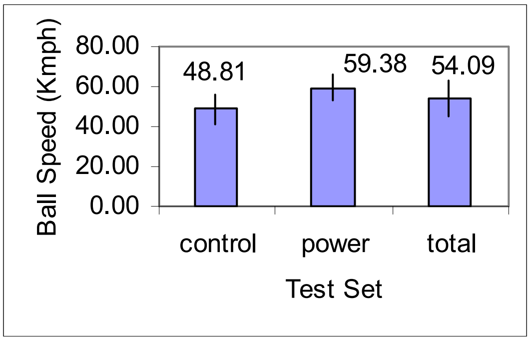


Figure 7.32 Accuracy (a) and Spectral RMS data (b) for racket 2

- **Racket 3**

Although many of the same trends are evident in racket three and the difference between the power and control sets is still statistically significant ($P<0.01$), figure 7.33 shows that the ball speed and accuracy data sets are more closely matched and display large standard deviation values. This might be attributed to the fact that racket 3 sits in the middle of the racket selection and is most likely to be of a similar feel to the racket before it. This ordering effect would mean that most players would experience a margin of change that might be difficult to detect thus creating more indecision and a larger spread of responses.

a) *b)*



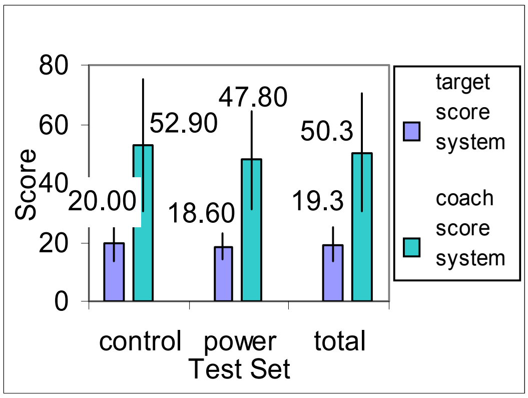


Figure 7.33 Ball speed (a) and accuracy data (b) for racket 3

- **Racket 4**

Many of the trends previously noted in racket configurations 1 and 2 are present in racket 4's data set. Figure 7.34 shows that, unlike racket 3, the difference in the average ball speeds for racket 4 each set is particularly clear ($P<0.01$).

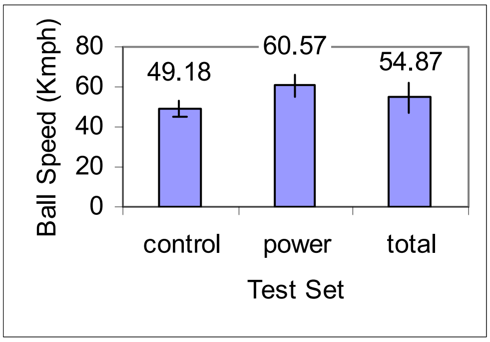


Figure 7.34 Average ball speed data for racket 4

- **Racket 5**

In figure 7.35 racket 5, like 4, demonstrates a clear differential between the power and control sets in as far as the measures of ball speed and accuracy are significant between the two sets ($P<0.01$).

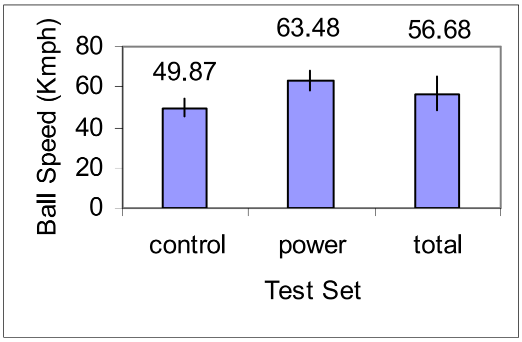
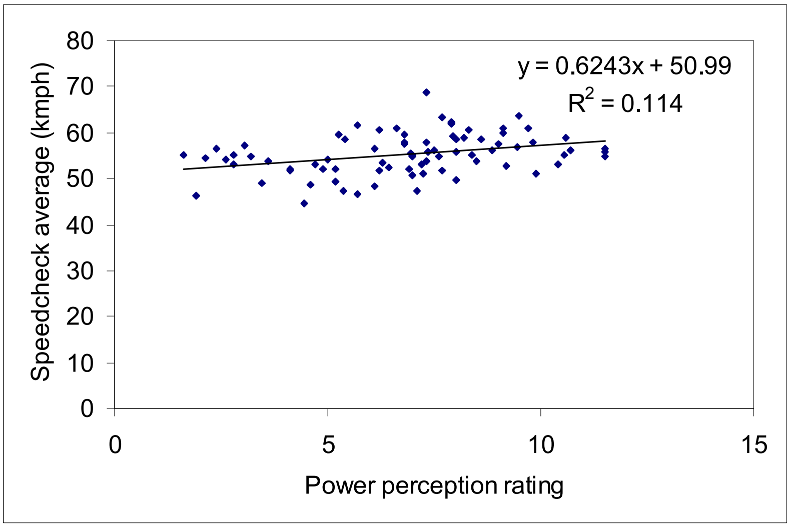


Figure 7.35 Average ball speed data for racket 5

7.2.5 Correlation analysis

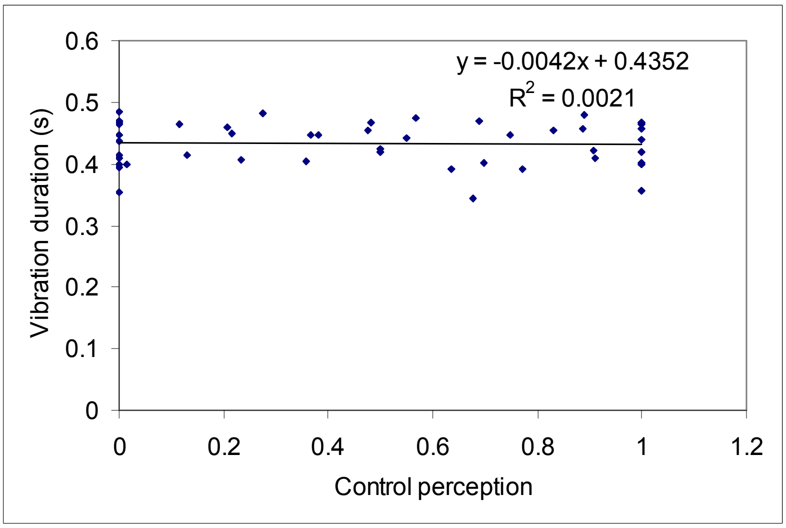
Each impact captured by the wireless data acquisition hardware was made up of 12000 data points, and with each of 20 participants undertaking an average of 144 impacts, and answering a set of 8 perception questions for each of 4 or 5 rackets, coupled with the objective accuracy and ball speed data amounted to a large volume of data to be processed and analysed. The wealth of data meant that there were many comparisons to be made between physical and perception measures. To highlight those comparisons most likely to exhibit some form of relationship correlation coefficients were calculated for the entire data set. Comparisons with correlation coefficients greater than |0.5| were plotted and examined in more detail. Since the correlation coefficient could not account for non linear relationships, a number of elements that might be expected to demonstrate some form of correlation were examined regardless of their respective coefficients.

Of the graphs produced many had low R^2 values and varying degrees of correlation could be observed in spite all having relatively high correlation coefficient values. A few examples of these are demonstrated in figures 7.36 to 7.38.



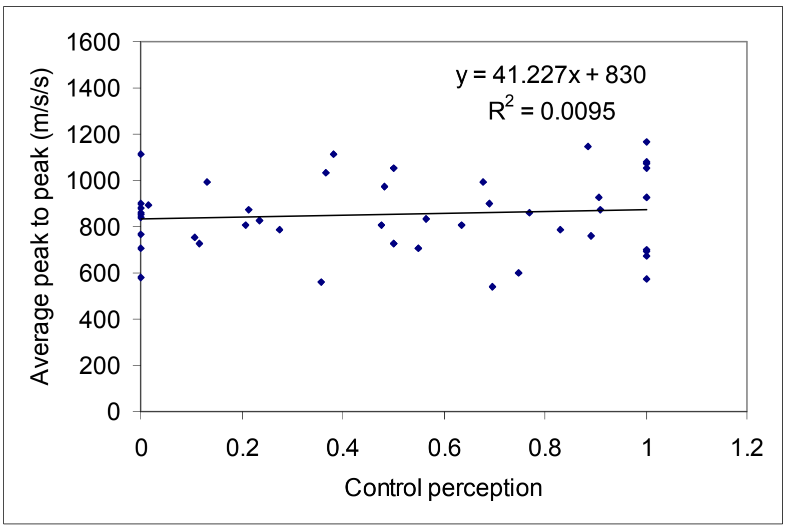
Correlation coefficient = 0.504

Figure 7.36 Average ball speed versus power perception



Correlation coefficient = 0.515

Figure 7.37 Power set vibration duration versus control perception normalised



Correlation coefficient = 0.519

Figure 7.38 Control set peak to peak data versus control perception normalised

The graphs in which some form of relationship could be observed still generally had low R^2 values, as can be seen in the figure 7.39.

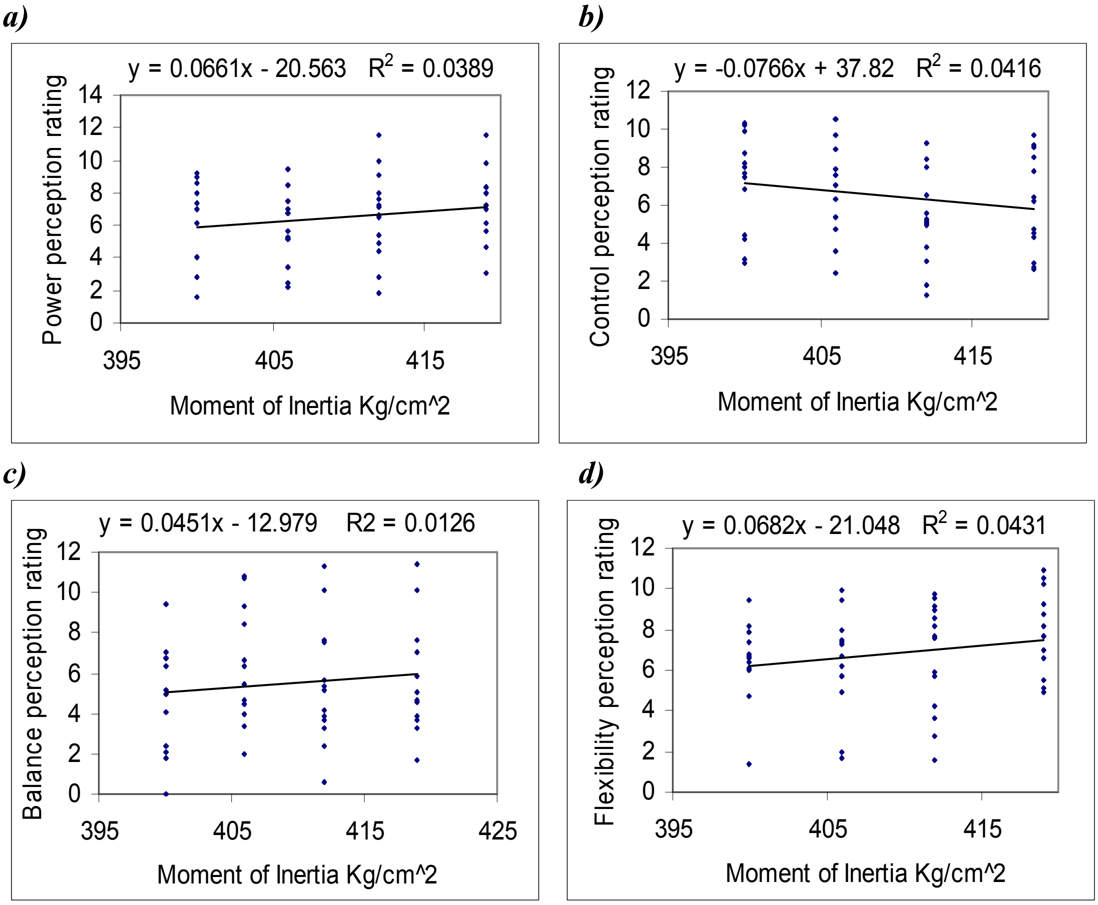


Figure 7.39 Examples of low R^2 values in perception data graphs a) Power perception b) Control perception c) Balance perception d) Flexibility perception

The low R^2 values were to be expected given the nature of the data means that there is a tendency for a high variance (Stroede 1998). It was clear that the R^2 values were not representative of the strength of the correlations so regression statistics were used to establish a statistical significance associated with the data trend line gradients. Table 7.3 indicates the confidence intervals of the strongest relationships for the four rackets with moments of inertia within the market range.

Table 7.3 Confidence intervals for the strongest relationships

Y	X	Correlation	P-Value	Confidence Interval
Power	Inertia	Positive	0.24	75%
Control	Inertia	Negative	0.39	60%
Balance	Inertia	Positive	0.21	70%
Flexibility	Inertia	Positive	0.14	85%

When the fifth extreme racket is included in the analysis these correlations become clearer and better defined statistically. Some previously undetected relationships also become evident with the inclusion of this racket, specifically weight and moment of inertia as can be seen in figure 7.40.

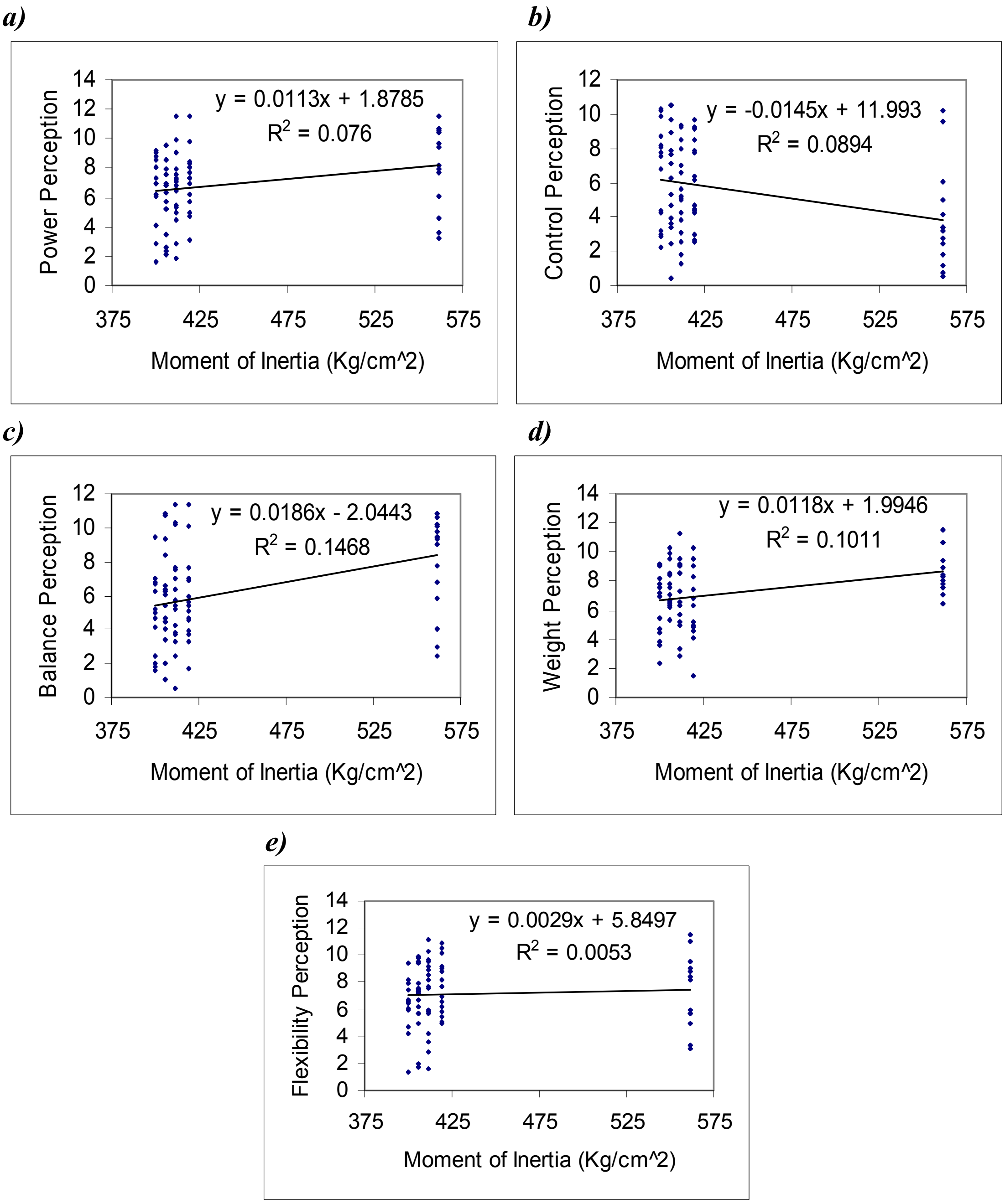


Figure 7.4 Perception graphs against moment of inertia including fifth racket data a) Power perception b) Control perception c) Balance perception d) Weight perception e) Flexibility perception

As expected the R^2 values remain low but table 7.4 shows the improved confidence intervals that are evident when the extreme racket is included.

Table 7.4 Improved confidence intervals with inclusion of the fifth racket

Y	X	Correlation	P-Value (2 sig. fig.)	Confidence Interval
Power	Moment of Inertia	Positive	0.031	95%
Control	Moment of Inertia	Negative	0.0027	95%
Balance	Moment of Inertia	Positive	0.0023	95%
Flexibility	Moment of Inertia	Positive	0.23	75%
Weight	Moment of Inertia	Positive	0.0018	95%

The low P-Values indicte that a relationship exists between the average listed player perceptions and moment of inertia (table 7.4). To ascertain more information about the indicated relationships, statistical ranking tests, as described earlier in the chapter, was employed. The rackets were ranked by their moment of inertia in order of the expected relationship, e.g. racket 5, with the highest moment of inertia configuration, was ranked to have the highest power perception rating, and also ranked to have the lowest control perception rating. These expected rankings were then compared to each player's perception ratings rank. The Spearman's ranking test calculates a coefficient to indicate the degree of correlation between the two ranks by taking the difference in each rank position from the expected rank position.

Within the 19 strong sample, ten participants had strong spearman rank coefficients of |0.6| or more for the majority of their perception responses. 12 of the sample had spearman rank coefficients of this magnitude for their swing ease responses, giving it the highest occurrence rate of the test set. More than 50% of participants also had spearman co-efficient values equal to |0.6| or more for power, control, flexibility and vibration perceptions.

The ranking coefficients could be used to filter out participants that could be deemed to be less skilled at perceiving racket qualities. The averages of the modulus of the coefficients were calculated, and those with values of |0.6| or less were removed from the data analysis. In essence participants, who appeared to rank the majority of their perception ratings in accordance with the physical changes in the racket, whether in a positive or negative relationship, were considered to be ‘skilled’.

The filtered data displayed in figure 7.41 shows how much clearer the correlations become. When only the 4 rackets with moments of inertia within the market range are considered (figures 7.41 (a), (c) and (e)) a positive or negative trend can be observed. The fifth extreme racket confirms that the correlations exist albeit with a flater gradient in each case. This flatter gradient suggests that, although the participants have been able to detect that this extreme racket is at one end of the range they have not been able to quite gauge the extent of the difference between it and the market range rackets. It is possible that if the test range was more evenly distributed players would have been able to more accurately assess the magnitude of the difference between the rackets rather than just being able to identify that one is far different from the others which would result in better defined correlations.

A slight ‘hump’ can be seen in the control perception rating data shown in figure 7.41 (a). The second data point might suggest there could be an inverted-U relationship emerging, although it is impossible to validate this with out further testing. Similarly figure 7.41 (c) and (e) seem to show a dip at the second data point possibly indicating a U-shaped relationship. If it were possible, through additional testing, to show that these relationships exist then it might be tempting to try to find an ‘optimum’ peak for these elements of racket perception.

When the power perception data shown in figure 7.42 (a) is initially examined it might appear as if the relationship has deteriorated when only ‘skilled’ participants are considered. However, figure 7.42 (c) to (e) show how the correlation is made up of a set of positive correlation data and a set of negative correlation data.

This observation suggests that some players perceive lower inertia rackets to be more powerful and some perceive higher inertia racket to be more powerful. This finding is mirrored by anecdotal evidence from players that believe their ‘game’ suits a head heavy or head light racket.

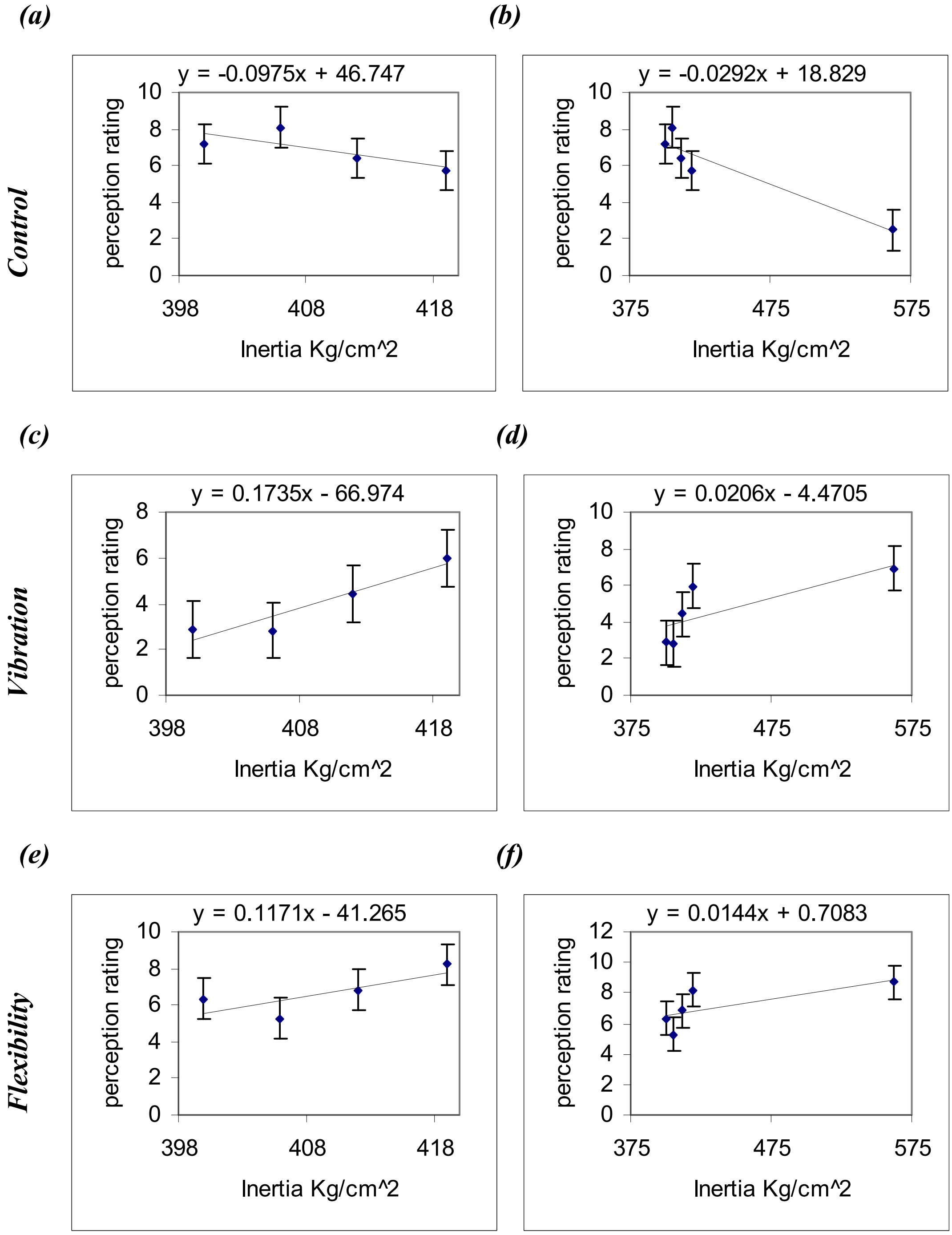


Figure 7.41 Graphs showing average data (± 1 SD) from a filtered sample group against racket moment of inertia (a) Control perception data for the 4 market range rackets (b) Control perception data including the extreme fifth racket (c) Vibration perception data for the market range rackets (d) Vibration perception data including the extreme racket (e) Flexibility perception data for the market range rackets (f) Flexibility perception data including the extreme racket.

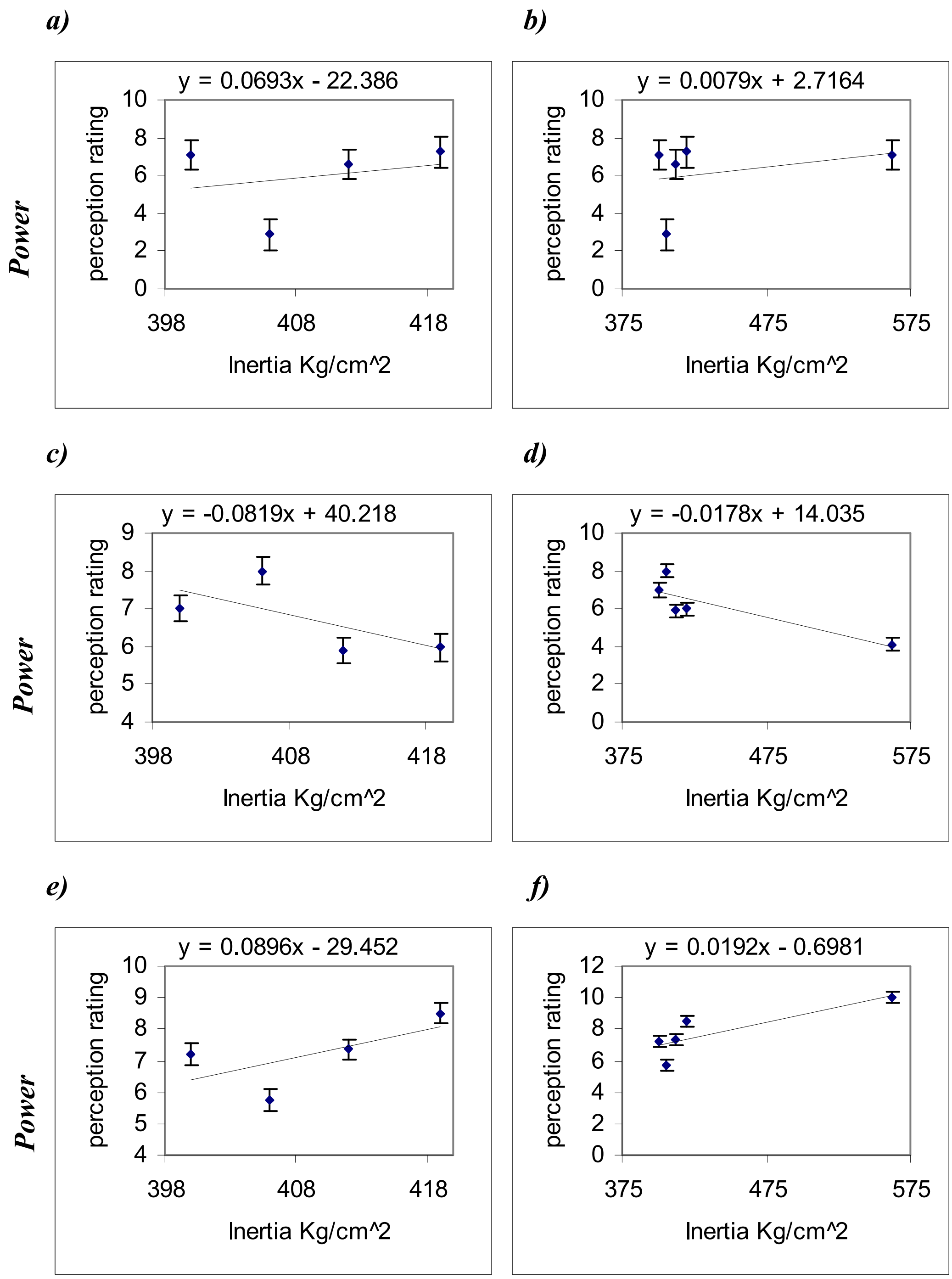


Figure 7.42 Filtered average power perception data (± 1 SD) versus racket moment of inertia (a) 4 market range rackets (b) All test rackets including fifth extreme racket (c) Positive correlation filtered sample showing 4 market range rackets (d) Positive correlation filtered sample including extreme racket (e) Negative correlation filtered sample showing 4 market range rackets (f) Negative correlation filtered sample showing including extreme racket

7.3 Summary

A general overview of the data would suggest that in some specific cases there does appear to be a visual relationship between some of the player perceptions and the changes in inertia of the racket. The R^2 values associated with the fitted trend lines were all very low, which was indicative of the high variance of the data that is to be expected when examining subjective data but was not reflective of the level of correlation that was present. To ascertain some form of statistical confirmation of the visibly recognisable relationships, regression and ranking methods were implemented.

Regression methods provided P-values and confidence intervals that could indicate the significance of the correlations that exist. Regression provided evidence that there was a positive correlation between power, balance and flexibility perceptions and a negative correlation between control perception, and the moment of inertia of the racket when kept within the common market range. When extreme inertia data is considered, these relationships are reinforced, and a stronger relationship with weight perception begins to emerge in the statistical analysis.

Ranking methods were used to show the frequency with which participants had ranked their perceptions of the rackets, either positively or negatively, in accordance with the changes in inertia. Ten participants had strong spearman rank coefficients of $|0.6|$ or more for the majority of their perception responses. More than 50% of participants also had spearman co-efficient values equal to $|0.6|$ or more for power, control, flexibility, swing ease and vibration perceptions.

With the exception of swing ease and vibration the perceptions with the highest ranking coefficients correlated with those which had the strongest confidence intervals.

Within the given sample the spread of data is very broad, and as such the correlations are not so clearly defined. This suggests that in general players are not able to definitively perceive performance differences when racket moment of inertia is changed within the experimental range. A more detailed analysis of some specific elements reveals some undeniable statistically significant relationships that become more apparent when the data set is filtered to only include players that are shown to be 'skilled' at perceiving changes by only selecting those that had spearman ranking coefficients greater than |0.6|. In some instances the data points seemed to suggest that non-linear trends might exist in the selected data. Further experimentation across a wider experimental range of moments of inertia would help to establish the existence of these trends. These non-linear trends could be particularly useful in a design context, since maxima and minima points can help to locate the 'optimum' range for a specific aspect of racket feel. Further testing investigating other racket characteristic could well produce similar trends perhaps in relation to other aspects of feel. In this way it would be possible, with successive testing, to gradually build a complete picture of how racket characteristics can be optimised to design the 'ideal' racket.

One of the main problems with drawing firm conclusions from the data is the inter- and intra-subject variability. Increasing the number of skilled participants by screening a larger sample should address this issue. A larger and more perceptive sample group should help to more clearly define the emerging trends and increase significance. Clearer correlations would be of more use to support design evaluation and to guide future development. Overall the test results have addressed one of the research questions by demonstrating a degree of correlation between objective and subjective measures and thus part of the hypothesis by substantially and usefully improving subjective assessment of tennis racket performance.

CHAPTER EIGHT

FATIGUE TESTING

8.1 Introduction

As discussed in Section 2.2.2, it is widely accepted that elite tennis players rarely suffer from lateral epicondylitus (tennis elbow) whereas it is relatively common in regularly active recreational players. It has been suggested by some researchers (Cooke et al. 2002) that one reason for the differences in the ability groups is the level of conditioning; the higher level players expected to have stronger musculature with better endurance that is less vulnerable to fatigue. Fatigue may be instrumental in the reduction of shot quality, increasing the likelihood of off centre impacts and potentially changing the stroke technique or dynamic grip response. It might also be reasonable to expect that fatigue would affect a player's perception of the 'feel' of strokes and the racket itself.

Although there is some existing research in the area, little or none of the published work specifically relates fatigue to tennis elbow or feel. Of the work that has been completed that relates fatigue to a tennis context, Bowyer (2003) suggests that local fatigue of the forearm musculature has little or no effect on player accuracy, although there is some doubt as to the extent of the fatigue experienced by the players Bowyer studied. Work by McCarthy-Davey (2000) showed full body fatigue to have a significant effect on tennis stroke accuracy. No data was collected on impact shock and vibration or grip response in this earlier study, making an assessment of how this relates to tennis elbow difficult.

A further experimental study would be useful to clarify the differences and relative importance of fatigue in a local and full body context in relation to tennis elbow injuries. The study presented in this chapter aims to test players to full body fatigue monitoring the players’ accuracy as well as measuring the impact shock and grip responses through out the tests.

8.2 Methodology

8.2.1 Experimental aim

The experimental application of the wireless data acquisition system presented in this chapter was intended to answer the research question:

> Do the more play realistic and generally fatiguing experimental protocols enabled by less intrusive instrumentation give rise to significant different performance excitation scenarios to those produced in unfatigued play?

The new level of freedom allowed by the instrumentation meant that a new protocol could be developed to more effectively induce full body fatigue. McCarthy-Davey, (1997) introduced a method of fatiguing participants involving over 90 minutes of simulated match play followed by a tennis hitting performance test requiring players to run to hit alternate shots from either side of the court at target boxes which continued until volitional fatigue. This was reported as being effective at fatiguing the players, but the test method was too long to be implemented in this instance. Bowyer (2003) implemented an accelerated fatigue protocol in which participants hit repetitive forehand and backhand shots in a predetermined sequence for set periods of activity and rest. Participants reported local muscular fatigue in the dominant arm over this relatively short test period. This method was more appropriate for the time restrictions of the current line of testing, but did not induce the full body fatigue required.

The multi-stage fitness test developed by the Loughborough University Department of Physical Education and Sports Science and is a widely accepted predictive measure of VO2max. The method requires participants to complete shuttle runs over 20m in time with a bleep that becomes progressively quicker every minute that the test continues. In effect the participant runs further each minute until they are unable to continue to keep pace with the bleeps on the tape. The participants generally will not be able to increase their speed once they have come close to or reached their VO2max which is accompanied by a maximum respiration and heart rate. The number of minutes and bleeps that are completed by the participant are thus indicative of their VO2max and predictive tables based of an extrapolation of population averages can be used for conversion.

The various methods discussed were all considered when developing a protocol more specifically appropriate to addressing the above research question. The test protocol needed to be able to achieve full body fatigue, within a time considered reasonable for testing and be representative of real tennis play. A hybrid protocol incorporating the best aspects of the Loughborough university multistage fitness test, McCarthy-Davey and Bowyer's work was developed, as described later in this chapter.

8.3 The Sample

The demands of a full body volitional fatigue test meant that the sample would have to be made up of physically fit and healthy participants aged between 18 and 40 years old. Previous studies suggest the sample size should be 10 or more participants to achieve statistical significance in the subsequent results analysis.

The physical nature of the testing meant that many aspects of physiology could significantly influence the results. With this considered, females were excluded from the sample group due to the physiological changes associated with the menstrual cycle that would be difficult to control. The males considered for the sample were also required to be of a suitable playing level so that they would be accustomed and suitably conditioned to the demands of such a test. The final sample used in the testing consisted of 8 male national or county level tennis players all aged between 18 – 24 years from the Loughborough University 1st team tennis squad.

8.4 Test Equipment

8.4.1 Equipment and Test Configuration

Unlike the perception testing described in Chapter 6 (Section 6.4.2), two different racket frames were used to compare the response of a typical tour player's racket, the Head LM Prestige and a typical recreational player's racket, the Head LM8. The properties of each racket were:

- Head Prestige racket frame
    - Weight 390g
    - Moment of Inertia 360 $kgcm^{-2}$
    - Length 68 cm
    - Width 26.5 cm
    - Strung with Prince synthetic gut at 60 pounds
    - Grip size 4 with Karakal PU Super Grip tape

- Head LM8 racket frame
    - Weight 368g
    - Moment of Inertia 398 $kgcm^{-2}$
    - Length 69 cm
    - Width 28.25 cm
    - Strung with Prince synthetic gut at 60 pounds
    - Grip size 4 with Karakal PU Super Grip tape

Both racket frames were adapted to accommodate the wireless data logger by hollowing out the grip allowing space for instrumentation and mounts. The rackets were strung with Prince synthetic gut to a tension of 60 lbs and gripped with black Karakal PU Supergrip. The racket frames were unchanged in any other way.

The SpeedCheck radar, accelerometers and FlexiForce sensors were all mounted, calibrated and set up as described in Chapter 6 (Section 6.4.2).

A Lobster ball machine was used feed balls at a set rate throughout the test. The feed was delivered straight down to the backhand side of the court similar to that detailed in Chapter 6 (Section 6.4.2).

A grid was marked out with tape around a marked target square located near the centre of the court where a recovery shot might be played (figure 8.1).

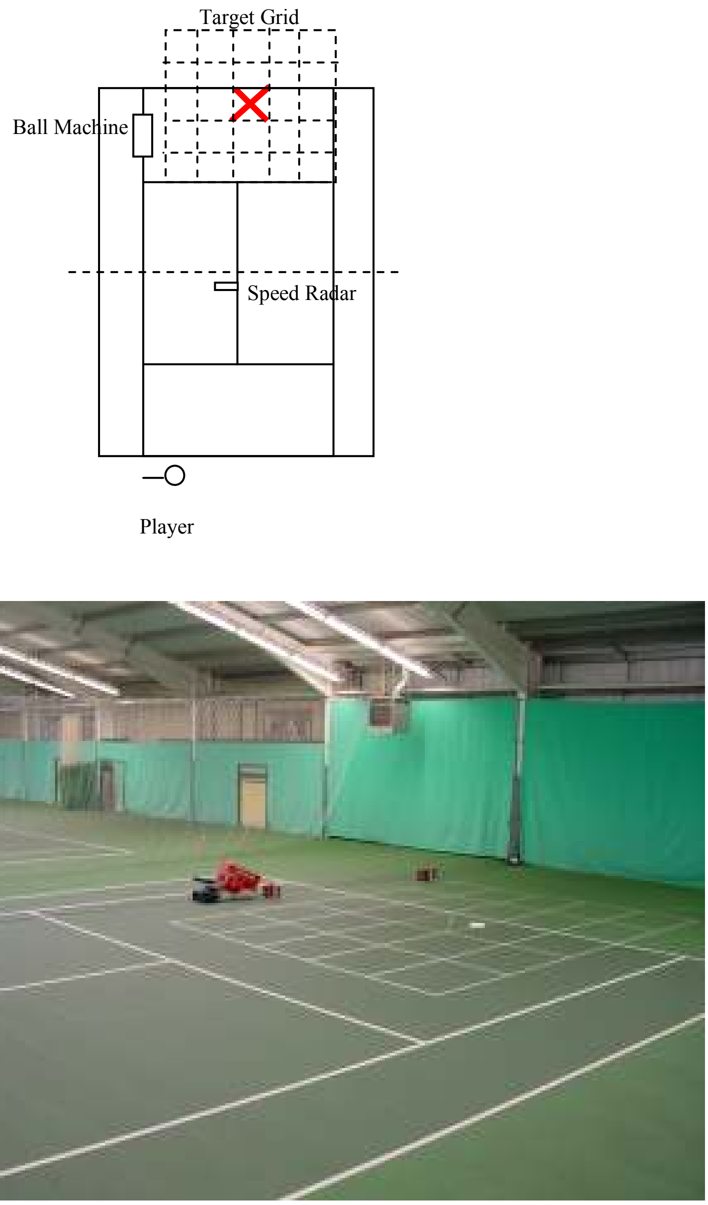


Figure 8.1 Crosscourt target area

The target square location was chosen based on consultation with a number of players and coaches who were generally of the opinion that when under pressure a player should play a recovery shot deep towards the middle of the court to reduce the attacking opponents' options to hit angles. Although there was some consensus that an error margin should be accounted for when playing the shot, the grid square closer to the baseline was selected as the target square to motivate each participant and to maintain consistency with accuracy assessment described in the literature.

Other factors (e.g. environment, balls, racket appearance) were kept constant as described in Chapter 6 (Section 6.4.4).

8.5 Fatigue Test Protocol

An overview of the test protocol is shown in Table 8.1

Table 8.1 Test Protocol

<table>
<tr><td>Participant filled out information sheets and consent forms</td><td>5 minutes</td></tr>
<tr><td>Thorough warm up and familiarisation of participant</td><td>10 minutes</td></tr>
<tr><td>Player instructed to hit balls towards the target grid and run to a level marker before hitting each subsequent ball</td><td rowspan="3">10 - 20 minutes</td></tr>
<tr><td>Each minute the level marker was moved 50 cm further away from the 'impact zone' making the participant run further and faster each minute</td></tr>
<tr><td>The participant continued until three consecutive balls were missed or volitional fatigue was achieved</td></tr>
<tr><td>Participant cool down</td><td>10 minutes</td></tr>
<tr><td>Participant thanked and asked for feedback</td><td>5 minutes</td></tr>
<tr><td>Total time</td><td>50 minutes</td></tr>
</table>

Given the high level of physical exertion experienced by each participant they were asked to conduct a thorough warm up and then asked to hit balls for one minute fed through the ball cannon at a fixed feed rate towards the back hand corner of the court that is referred to as the 'impact zone'. The player was instructed to hit backhand recovery drives towards a target area to familiarise them to the ball feed.

After one minute rest the player was requested to hit balls in the same fashion, this time touching a marker with their foot at a point on the base line such that the player needs to run back and forth some distance across the base line. This served as an additional warm up and familiarised the player to the nature of the test.

Each minute the marker was moved 0.5 m further from the impact zone so that the player has more distance to travel between shots. This continued, every minute increasing the distance of the marker from the impact zone, until the player missed three consecutive balls or reached volitional fatigue. The test racket was used to monitor the changes in impact shock and grip response during the fatiguing process via the wireless device located in the grip of the racket. Ball speed, accuracy scores, perceived exertion scores and heart rate were also monitored throughout.

The test was conducted twice with each participant, once with the tour racket and once with the recreational racket to compare the effect of each. Tests were separated by at least 7 days rest, with half the sample using the rackets in reverse order.

8.6 Evaluation of Testing

Only 8 of the intended 12 strong sample were tested and of those only 2 were able to be tested with both rackets before the wireless data logger malfunctioned and testing had to be abandoned due to time restrictions. Of the data sets that were collected 5 were incomplete or corrupt due to the problems experienced with the failing wireless device. The device was diagnosed to have a fault with the bios that became corrupted when the battery power dropped below a certain level. The device was reconditioned to account for the fault, but not in time to complete the testing within the window of opportunity imposed by player availability. The limited data set was sufficient, however, to provide some evidence of trends and indicate the success of the protocol.

8.7 Summary of Raw Data

VO2max refers to the maximum level of oxygen uptake per unit weight that can be achieved by the body. The body's VO2max is dependent upon its ability to take oxygen from the air and transport it to and utilise it in muscle tissue. Haemoglobin in the blood is responsible for the bulk of oxygen absorption and transportation; to increase the volume of oxygen utilised by the body, heart rate must increase to pump higher volumes blood to the lungs and muscle tissue. When the heart can work no harder the body is unable to utilise any more oxygen, thus maximum heart rate is one of the limiting factors of oxygen uptake. It is widely accepted that heart rate is proportional to VO2 with increasing work rates (Wilmore and Costill, 1999), as the body reaches VO2max, a plateau can be observed in a graph of heart rate as it also becomes maximal.

The heart rate data for each participant steadily rose to a plateau near their predicted maximum heart rate indicating that the player was likely to be at or near their VO2max (figure 8.2)

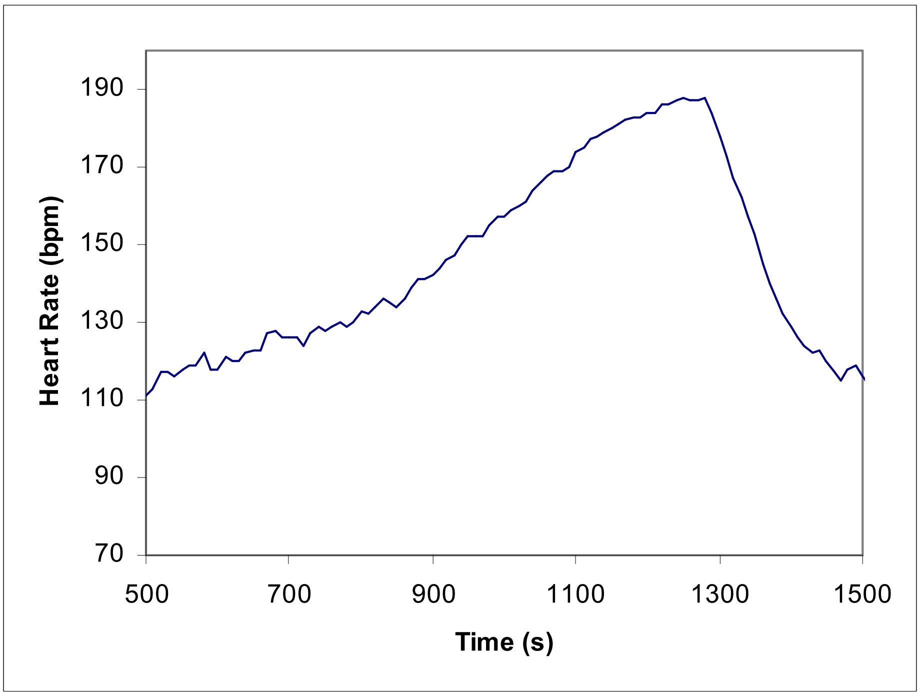


Figure 8.2 Player heart rate reaching maximum plateau at volitional fatigue

Figure 8.3 shows how the rating of perceived exertion (RPE) data closely followed the heart rate data for all participants and confirmed that the participants were experiencing high levels of fatigue. Figure 8.4 shows a graph comparing RPE and heart rate for a single participant from a complete trial within one of the instrumented rackets. Similar results were observed for each participant.

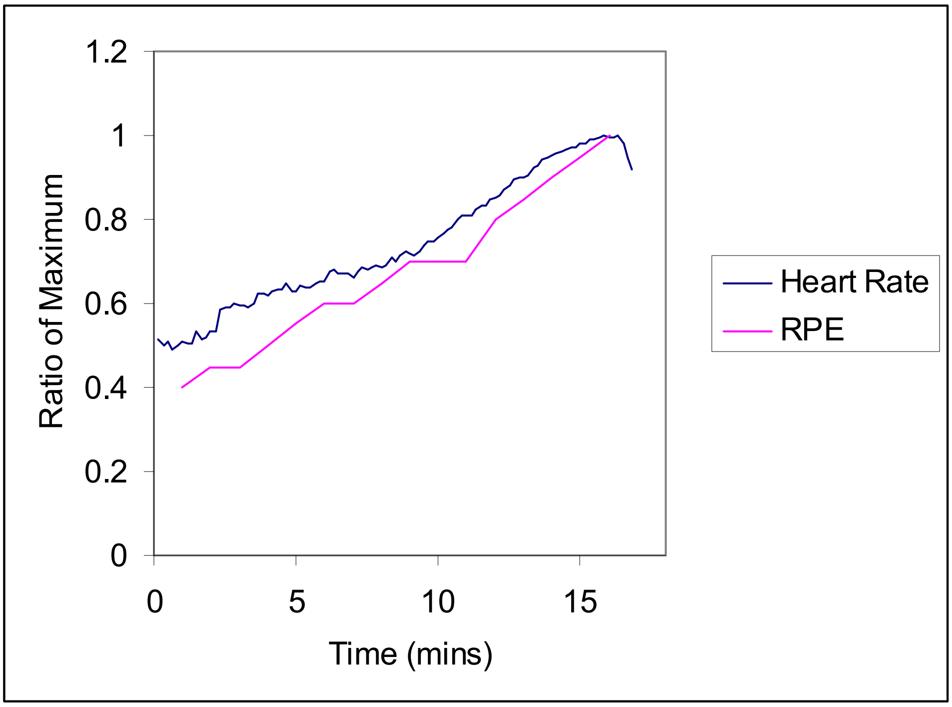


Figure 8.3 A comparison of RPE rating of perceived exertion and heart rate for one participant during a single racket test

Typically each impact trace throughout the fatigue tests had a preliminary rise, attributed to the racket swing, followed by an impact spike and subsequent vibration decay. Figure 8.4 shows 2 typical traces from the beginning and end of a fatigue test.

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

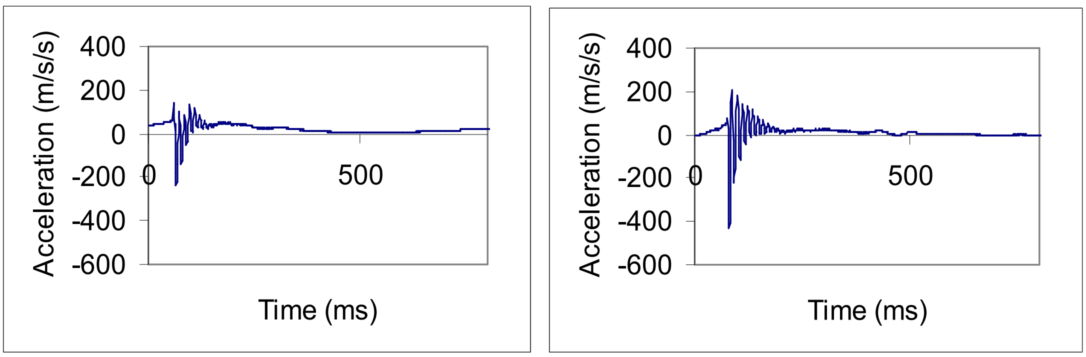


Figure 8.4 Typical impact traces from the beginning (a) and end (b) of fatigue testing

8.7.1 Wireless data logger processing method

The raw accelerometer data was processed as reported in Chapter 7 (Section 7.1.1) with measures calculated for peak to peak, vibration duration and spectral RMS.

8.7.2 Accuracy Data Processing

Unlike the perception testing, the target grid in this case was located more centrally on the court. This meant that the coach's scoring system develop for the perception tests would not be relevant to the fatigue study. Thus, only the symmetric target score system described in Chapter 7 (Section 7.1.3) was used.

8.7.3 Results Analysis

Participants hit 14 or 15 shots in each level of the test. Average peak to peak acceleration values taken from all impacts for each level of the fatigue test revealed that the majority of the participants experienced higher magnitude peak to peak acceleration for the normal tri-axial accelerometer channel towards the end of the test compared to that in the earlier levels ($P<0.05$). Higher peak to peak values tend to be indicate off centre hits as demonstrated by the higher angular accelerations, thus the data suggests that the players were hitting more frequently off centre as they fatigued. The average peak to peak acceleration values from the normal accelerometer channel were generally mirrored in the angular rotation about the polar axis, with higher magnitudes in the later levels. In the transverse and longitudinal channels the trend was not apparent. Figure 8.5 shows examples of the trend towards higher average peak to peak acceleration values from the normal tri-axial accelerometer channel evident with most participants as they experienced higher levels of fatigue.

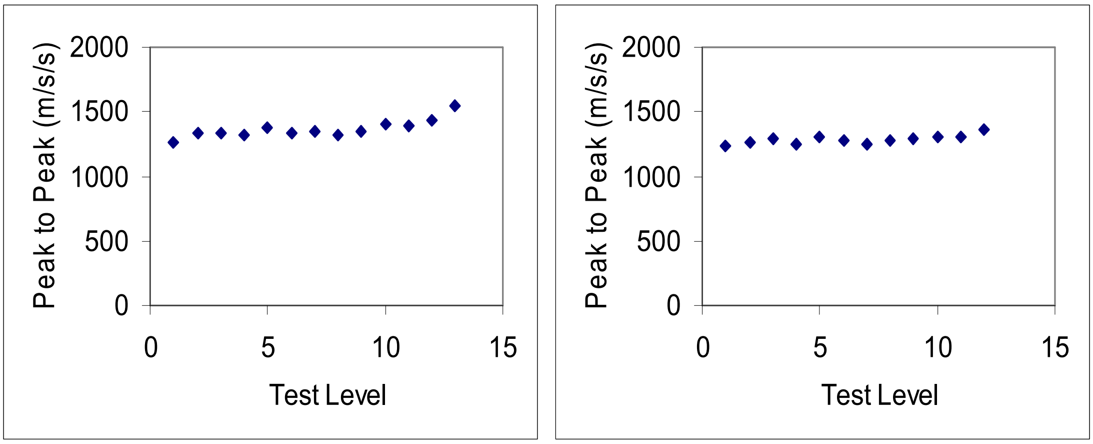


Figure 8.5 Sample average peak to peak traces showing higher values toward the end of the test

In one case the early levels demonstrated elevated average peak to peak values. These levels dropped as the test progressed, but rose again towards the later levels as the participant experienced higher levels of fatigue (figure 8.6)

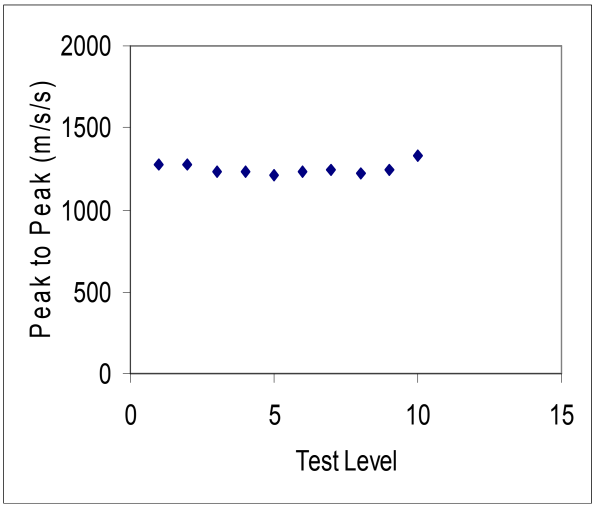
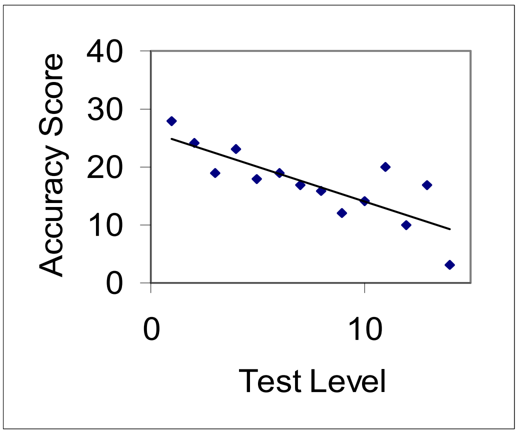


Figure 8.6 Average peak to peak measures for a player with high values in the early levels

The higher average peak to peak values in the earlier levels of the test for this individual could be the result of a number of factors. At the early stages of the test the player does not have to move so far and may be better balanced and positioned, thus able to produce more power with each shot, which would result in the higher values observed. Perhaps more likely is the fact that the racket used by the participant is probably unlike their normal racket and it might be expected that whilst they are unfamiliar with the feel and behaviour of the racket they would make more errors and experience a higher frequency of off centre hits. As they become more accustomed to the racket they are able to hit more consistently again until, as they begin to fatigue, they are unable to achieve the same quality of shot and begin again to hit with a higher frequency of off centre shots.

Analysis of the existing accuracy data displays a substantially reduced accuracy in the later levels as the players fatigued. In each case the total accuracy score for the later levels falls below 25% of the maximum. Figure 8.7 shows the accumulated scores for each level for two typical participants.

participant (a) ***participant (b)***



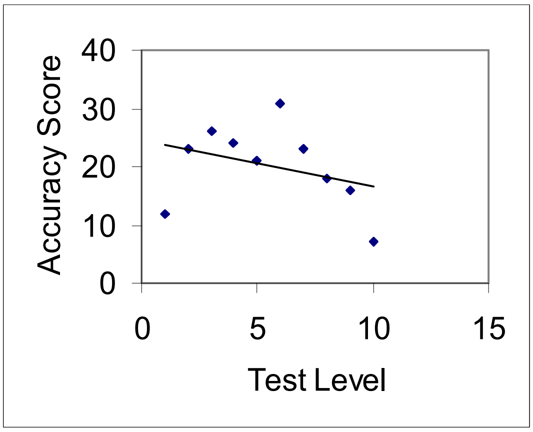


Figure 8.7 Sample accuracy score graphs

Since a player is likely to be considerably less accurate when they hit off centre, the data supports the evidence of increased frequency of off centre hits provided by the peak to peak acceleration data. The initial lower score at the beginning of the test that can be observed in graph (b) is similar in form to that noted in figure 8.5 for the average peak to peak values. It would appear that the player undergoes a similar familiarisation process in the early levels, then hits competently for a time before becoming fatigued when performance derogates again.

The original aim of the fatigue testing was to compare the effect of fatigue on a player using two different racket types. Of the 5 complete data sets, 2 were collected from a single participant using each of the racket types tested: a tour player's racket (Head LM Prestige) and a recreational player's racket (Head LM 8). A comparison of the peak to peak acceleration data between the different rackets for this single player shows that overall lower values were measured for the recreational racket ($P<0.01$), and a smaller increase was observed as the player fatigued when compared with the tour racket values. Figure 8.8 compares the peak to peak data for each racket type.

(a) *(b)*

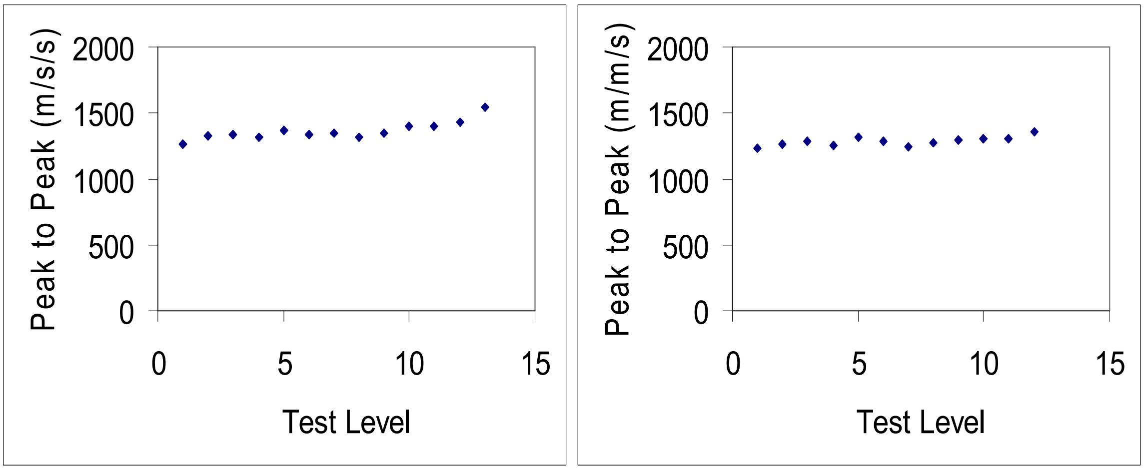


Figure 8.8 Comparison of peak to peak values for (a) tour racket and (b) recreational racket

It is possible that the higher polar inertia of the recreational racket resulted in the reduced overall values and made it less sensitive to off centre impacts resulting in a smaller increase in the values as the player fatigued. It is also worth noting that the participant was able to continue hitting for an additional level when using the tour racket and the increase in peak to peak acceleration values at the earlier equivalent level are more comparable. To complete the higher level requires the player to hit 14 or 15 more balls, run for a further minute at a higher pace travelling an additional 91 to 98 metres. The higher level reached when using the tour racket might suggest that this racket is less fatiguing to use than the recreational racket, which might be attributed to its better manoeuvrability, or ease of shot production for example. It might also be attributed to the psychological effect of a less familiar racket with the participant less willing to endure discomfort of fatigue and when coupled with that of the racket.

Of course the data should be treated with caution since only one participant could be considered and there may be some degree of ordering effect. Since the player conducted the first test with the tour racket, and the recreational racket a week later, it might be suggested that the player was not sufficiently recovered in this time which might explain the reduction in performance the following week. Although this is unlikely since it is well documented that the bulk of recovery occurs in the first 48 hours after exercise, and exercise and diet were controlled to some extent, it is possible that the participant might have been experiencing the early stages of illness or injury, sleep deprivation or some other form of psychological effect such as stress all of which can contribute to a reduction in performance.

8.8 Summary

The fatigue study was terminated before its completion and of the sample that was tested some of the data was corrupted by the failing wireless device. As a result the main experimental aim could not be fully achieved, although the data that was captured was able to answer the main research question.

> Do the more play realistic and generally fatiguing experimental protocols enabled by less intrusive instrumentation give rise to significant different performance excitation scenarios to those produced in unfatigued play?

The analysis of the data generated was used to demonstrate the success of the protocol and indicated that there may be some emerging trends worth further investigation.

The protocol was intended to induce accelerated fatigue. The results of the heart rate and RPE showed that the test was capable of taking participants to or near their VO2max and so was successful in achieving this high level of fatigue within the test time frame.

The majority of the complete accelerometer data sets displayed higher average peak to peak acceleration values towards the end of the test as the participant reached the later stages of fatigue. Although Glynn (2007) reports that vibration in itself is not likely to be a contributing factor to tennis elbow or other injury, and that off-centre or mistimed impacts are more likely to be responsible, the higher peak to peak values are in themselves indicative of off centre impacts. Thus it appears, from the tested sample that players are hitting a significantly higher frequency of off centre impacts as they become fatigued ($P<0.05$) and potentially exposed to a higher risk of injury as a result. This might also explain why highly conditioned elite tennis players report less incidences of tennis elbow when compared to less conditioned recreational players that are more susceptible to fatigue.

A comparison of racket type was made for the only participant to use both the recreational and tour racket. Significantly higher peak to peak acceleration values ($P<0.05$) were evident in the tour racket which can be explained by the higher polar moment of inertia of the recreational racket. This quality could also reduce the sensitivity of the racket to off centre impacts which would help explain the smaller increase in the peak to peak values when compared to the tour racket as the player became more fatigued. It is interesting to note that the player was able to complete an additional level of the test when using the tour racket, which might go someway to explain the difference in the observed increase in peak to peak acceleration values. It might also be concluded that the tour racket was less fatiguing to use than the recreational racket for this player.

Obviously with a sample of only 4 players and 5 data sets it is difficult to establish statistical significance in any trends that can be extrapolated to a larger population. Additional testing with more participants should verify whether the trends that have been shown to be significant in individual cases from the existing data hold for a more wide scale population. Since it is potentially only those that commonly suffer from tennis elbow that are exposed to higher risk of injury as they fatigue it might be necessary to consider specific cases as is common in medical pathology research. It is clear in any case that the protocol has been established as a valid method for future fatigue related phenomena testing.

CHAPTER NINE

DISCUSSION AND CONCLUSIONS

9.1. Introduction

The research presented in this thesis principally investigates the following hypothesis:

> Through the use of non invasive instrumentation and improved player perception elicitation techniques it is possible to substantially and usefully improve the objective and subjective assessment of tennis racket performance in play to enable investigation of better design characteristics and fatigue related injury phenomena.

To test the hypothesis, 4 research questions were devised relating to:

i. A conceptual model of player perception
ii. Instrumentation development
iii. The relationship between subjective and objective measures of racket performance
iv. The effect of fatigue on the player

Each is addressed in the following sections.

9.2. Perception relationship model

> What is the conceptual model used by players to assess and express their perception of tennis racket performance?

To establish such a conceptual model, interview testing was conducted to elicit vocabulary and reveal any interdependency relationships that exist between the perception phenomena. Feel map This resulting vocabulary was classified into groups of closely related quotes called 'nodes'. These nodes were linked to hubs called 'base themes' and lower order 'sub themes' which linked related nodes together. In turn related base and sub themes were linked together via higher order hubs known as 'general dimensions' forming clusters representing the 12 major tennis racket performance related perceptions listed below.

i.	Sound	vii.	Flexibility
ii.	Grip	viii.	Anticipated Use
iii.	Power	ix.	Cosmetics
iv.	Control	x.	Inertia Properties
v.	Feedback	xi.	Physiological Effect
vi.	Racket Dimensions	xii.	String Bed

Interdependency links were introduced to the structure to describe relationships between aspects of the map that the vocabulary indicated had interrelated affects. The 12 dimensions and the associated structure formed a network map or 'feel map' consisting of 210 nodes, 63 base and sub themes, and 54 interdependency links (Appendix 8). This map provided an insight into player perception but did not represent the complete model of player perception relationships.

Online questionnaire

To complete the model data was collected from 137 participants that responded to an on-line questionnaire. The online questionnaire asked participants to select vocabulary they were accustomed to using when describing particular elements of racket perception. Another section of the questionnaire assessed the relative importance of many of the 12 general dimensions and selected base themes revealed in the model. The final section of the questionnaire collected player responses referring to their perception of 'ideal' racket characteristics. The data acquired through this process was compiled into a weighted lexicon that enabled the user to look up node categories to find further examples of vocabulary use and any associated questionnaire data. The questionnaire data was represented visually in the feel map so that the whole model could be used quickly and easily with the lexicon only necessary to seek further detail.

Perception relationship model

The model was ultimately limited by the fact that some sections of the model had to be left without data due to time restrictions imposed upon the online questionnaires data collection. The initial map was based upon interviews with a limited number of participants and so the information presented may in some cases be specific to a small group or individual, and not representative of a wider population. Where data does not exist in the model it is not possible to differentiate which elements can be regarded to be in common use and how important they are to player perception. It is important to note, however, that on the whole the structures of both the German and English maps were very similar and it is merely the differences in method of expression not the meaning or definition that would be highlighted by additional questionnaire data.

At present the perception relationship model does not incorporate any additional data to indicate the validity of interdependency links. Whilst the links were only introduced where participants indicated they might exist, to confirm that they are in fact dependent upon each other a series of perception tests, similar to those conducted in the case of moment of inertia, would have to be conducted to investigate specific relationships between perceptions and their dependence on physical changes in the racket.

The model can be a useful tool acting as a research guide or design aid with relative importance ratings assisting with prioritization of issues and interdependency links indicating which additional factors should be considered or exploited for their influence on the characteristic area in question. The research sponsors and collaborators, Head Tennis, have already used it for this purpose. It can also be used help to construct more informed test questionnaires that utilize vocabulary that is more familiar to the player thus reducing the risk of participants misinterpreting the questions or rating scales. The value of the perception relationship model was further demonstrated by using it to produce player test questionnaires to support the other research presented in this thesis.

Improvements in technology and progressive marketing as well as changes in society as a whole mean that language is continually adapting and changing. This may mean that the model becomes less relevant as time goes on. In 10 or 20 years time, without revision, the model could become misleading. To keep the model up to date it is recommended that periodic interviews are conducted with a minimum of two players. If the model is still relevant then no new themes should emerge from the interviews. If new material does begin emerge, then it should be included in the model. With frequent maintenance in this way it should be possible to keep the model up to date for the most part. Since it is very unlikely that the underlying phenomena or sensory abilities of the players will ever change the model structure itself should need little or no maintenance. It is more likely the phrases used will change with fashion and in these cases additional or replacement nodes may be required to keep the vocabulary up to date. Regular maintenance should help avoid the unlikely event of a large scale rebuild of the model being required.

Summary

Overall the perception relationship model addresses the original research question since, with the exception of the few areas not considered by the online questionnaire, it represents the conceptual model used by players to assess their perception of the tennis racket.

Before the existence of this model the concept of feel was less well understood. With this model subjective assessment of racket performance can be more focused, more accurate (through the use of appropriate vocabulary and terms of reference) and more insightful (since the responses have greater meaning). Thus, at least the associated aspects of the original hypothesis are proven in the positive:

> Through the use of improved player perception elicitation techniques it is possible to substantially improve subjective assessment of tennis racket performance in play to enable investigation of better design characteristics.

9.3. Instrumentation Development

> Can the modern tennis racket be instrumented in an entirely un-intrusive manner so as to make possible multiple simultaneous measurements of critical performance phenomena without inhibiting prolonged real play use or compromising or biasing a player’s perceptions of racket behavior?

The process of answering this question began with a revision of existing racket instrumentation systems. With nothing reported in the literature that would completely satisfy the requirements of the research presented in this thesis a design specification was devised that could be used to develop a more appropriate system. It was apparent that a discrete wireless system would be best able to meet the requirements of the research. Given the protracted time required to build such a system a second wired system that utilised 'off the shelf' technology was constructed during its development.

Wired system

The wired system utilised readily available components that could be easily replaced. Although easy to maintain and very adaptable, this system restricted the range of movement of the player to the length of the 15 m wires from the computer, and necessitated an aluminium throat mounted bracket which significantly altered the inertia of the racket. Despite its shortcomings the wired system was used to good effect to pilot test protocols and test equipment to find appropriate levels of noise filtration and sensitivity whilst the wireless system was still in development. It was also used successfully to support the research activities of Bowyer (2003) and Glynn (2007).

Wireless system

The final version of the subsequent wireless data acquisition unit was small and light enough to be inserted into the grip of a racket. Consequently it was well concealed and had less effect on the player as well as offering new mounting options for the associated instrumentation. A revision of the aluminium bracket mount replaced the grip's outer covering PU foam and butt cap. The newly integrated mount and grip was lighter and concealed all the instrumentation within the grip sleeve and a bulbous 'butt cap' end rather than leaving it conspicuously exposed on the throat of the racket. The resulting 'smart racket' embodied solutions to many of the outstanding design problems.

The early versions of the wireless system experienced a number of problems with corrupt and noisy data. When the device battery power dropped below a threshold level of charge the bios became corrupted which rendered the device unusable and meant that any captured data stored on the device was unrecoverable. Analysis of the grip force data also revealed high levels of noise and interference in the signal. The specific cause could not be resolved for corrected use within the available timescales and the interference was so considerable that much of the data was undecipherable rendering the grip force channels ineffective.

Substantial improvements were made from the first iteration but the final version of the wireless system still experienced problems with the grip force channels and although the BTI devised a method of protecting the BIOS some reliability problems were still evident with very occasional power failures interrupting capture.

The ‘smart racket’ did satisfy the design specification as follows:

- **Measure types:** An inbuilt tri-axial accelerometer and 3 channels for uni-axial accelerometers mounted enabled acceleration measurement with 6 degrees of freedom and although grip pressure measurement was eventually abandoned 2 channels for FlexiForce sensors positioned to measure the most active areas of the player’s grip the system were provided for in the racket.
- **Resolution and sample rate:** 12 bit resolution and up to 3277 Hz sampling rate allowed appropriate levels to be set that were sufficient to conduct a frequency analysis and obtain peak to peak acceleration values
- **Period of Capture:** the 4 hour capture time was ample to conduct multiple trials without the need to interrupt the test protocol to download data.
- **Size and Weight:** the hardware weighed around 20 g and was contained in packaging small enough to fit within the racket butt and was mounted along with instrumentation in a discrete grip mount that replaced the original PU foam grip on the racket so had very little impact on the rackets’ characteristics.
- **Aesthetics:** the newly developed mount and smaller device meant that the wireless system was well concealed and, with the exception of a more bulbous shaped butt cap, was very similar in appearance to an un-instrumented racket.

The wireless system was ultimately shown to be a useful development for the research, greatly increasing the diversity of application and a number of examples of the experimental use of the system demonstrated in this thesis (Chapter 6 and Chapter 8). Given the experience of testing and the resulting performance of the device the wireless system might be improved as follows:

- Reliability of the system could be improved to ensure no data would be lost due to a malfunction
- Fully functioning grip force channels would improve and broaden the application of the system
- The integrated grip mount would be more discrete if smaller accelerometers could be found and contained within the dimensions of the manufactured butt cap.

Each of these improvements can be practically achieved and are discussed further in Chapter 10. More radical changes could be made given time to develop the system appropriately, these might include:

- Motion analysis capability built into the system to allow any adaptations to players' technique to be monitored
- Grip force sensors sufficient to cover the whole grip would provide a wider picture of grip force activity and would reduce any restriction on shot or grip type.
- Real time remote transmission of the data or buffered transfer between shots would allow performance of the player and the instruments so that intervention would be possible to correct any problems and could be adapted to become a coaching aid or to monitor risk of injury.
- The range and number of sensors could be increased to help monitor other elements of performance such as player muscle activity via EMG.

Although in its current state it is almost entirely unobtrusive it would also be beneficial for the system to be completely so. For this to be achieved the instrumentation would have be embedded entirely within the confines of the racket frame and its weight and strength equal to that of the material removed to house it. It is conceivable that improvements in materials and electronic technologies would allow this vision to be achieved for rackets available on the current market. The racket's external dimensions are unlikely to alter dramatically and the instrumentation required to be house is likely to reduce in size as technology advances allowing the system to be comfortably contained within the racket frame. The reduced weight and improved strength of instrumentation should also allow them to be more and more closely matched to the weight and strength of the material removed from the tennis racket in its current form.

Summary

Although imperfect the final version of the wireless data acquisition based instrumented 'smart' racket substantially proves that a racket can be instrumented in an unobtrusive manner so as to make possible multiple simultaneous measurements of critical performance phenomena without inhibiting prolonged real play use or compromising or biasing a player's perceptions of racket behavior.

The 'smart racket' is a substantial progression from other reported tennis racket instrumentation systems; most of which were far more intrusive or provided less comprehensive measures of performance. This has allowed more realistic simulated play experimentation, providing greater insight into racket performance and player/racket interactions whilst minimizing any inhibition of the player's natural technique. The 'smart racket' contributes further evidence that has proven the related aspects of the original hypothesis in the positive:

> Through the use of non invasive instrumentation it is possible to substantially and usefully improve the objective assessment of tennis racket performance in play to enable investigation of better design characteristics and fatigue related injury phenomena.

9.4. Perception Testing

> Can subjective player perceptions be correlated to objective performance measurements to enable design optimization leading to superior rackets?

Moment of inertia was selected as the most appropriate and relevant racket characteristic to investigate the relationship between objective and subjective measures. Moment of inertia presented itself as a viable variable with anecdotal evidence to suggest it has a considerable influence on performance and feel.

Methodology

A test racket was configured to use the wireless data capture system with lead tape moved to predetermined locations on the racket frame to adjust the moment of inertia. The perception relationship model was used to prioritise areas of interest and identify vocabulary most familiar to participants to create a test questionnaire. This questionnaire was used to collect player perception data alongside objective measures.

A test protocol utilising these tools was developed that was used to verify and define interdependency links indicated on the feel map. The perception test protocol, in this case examining moment of inertia, was intended to be a consistent methodology that could be adapted to investigate a range of different racket characteristics. Unlike other methods reported in the literature this approach not only combined the use of subjective and objective measures but uniquely also captured data from real play situations. The perception testing successfully demonstrated one application of this methodology.

Results

5 different moments of inertia were used in the experimental study, 4 of which were kept within the available market range with a 5th 'extreme' moment of inertia that was more than 33% higher than the market range. The resulting data displayed rather a wide spread, with the data range of up to 11.4 (99%) spread almost across the full scale and standard deviation values of up to 2.9 (25%), making it difficult to identify trends. In some specific cases there did appear to be a relationship between some player perceptions and the changes in moment of inertia of the racket. Regression

methods provided P-values and confidence intervals that indicate the significance of the correlations that exist. These methods provided evidence that there was a positive correlation between power, balance and flexibility perceptions and a negative correlation between control perception and the moment of inertia of the racket when kept within the common market range. When the extreme moment of inertia data was considered these relationships were reinforced, and a stronger relationship with weight perception emerged in the statistical analysis.

Although participants' feedback was generally positive, the broad spread in the perception data might indicate that players were distracted in someway, perhaps by the ball cannon, the instrumentation or the examiners that were present. When individual cases were considered, it seemed that some participants were able to perceive the changes in the racket performance better than others. This might suggest that either some of the participants were more vulnerable to distractions or that some individuals were merely better at perceiving the changes.

When the data was filtered to only include participants 'skilled' at perceiving changes by selecting those that had Spearman ranking coefficients greater than |0.6| more clearly defined and statistically significant relationships become more pronounced for some specific elements. Extrapolations of the correlations suggest some emerging U and inverted-U trends although further experimentation across a wider experimental range of moments of inertia would be needed to validate this finding. If these trends can be shown to exist they may be particularly useful in a design context with maxima and minima points able to help to locate the 'optimum' range for a specific aspect of racket feel.

Further testing investigating this and other racket characteristics might well produce similar trends perhaps in relation to other aspects of feel. In this way it would be possible, with successive testing, to gradually build a comprehensive picture of how racket characteristics can be optimised to design the 'ideal' racket. The experiences gained from the testing presented in this thesis suggests that the test sample required to achieve this ideal picture would have to be both larger to provide more data points and selective to only include players that are more skilled at perceiving racket feel.

Summary

Although it appears that Kreifeldt and Chuang (1979), Beak et al (2000) and Brody (2000) have reported conflicting data concerning the human perception of moment of inertia, it seems that the results presented in this thesis can support each finding and offer an explanation as to the differences reported in the literature. When the sample group is considered as a whole the data spread is very wide and it is difficult to find many distinct correlations which would support Kreifeldt and Chuang's (1979) finding that humans are only sensitive to changes in moment of inertia greater than 25%. However when the sample was filtered to only include players who had spearman coefficients of more than |0.6| and thus deemed to be more 'skilled' at perceiving racket feel, the data became better defined and trends could be observed that indicated that the players were sensitive to changes in moment of inertia of less than 4% supporting the work presented by Beak et al. (2000) and Brody (2000). Ultimately the results suggest it is the skill and experience of the participants that seems to dictate a participant's sensitivity to changes in moment of inertia of a tennis racket.

Aside from the results analysis the testing also demonstrated the application of a protocol that could be adapted to test a variety of racket characteristics, or indeed even other sports implements. Filtering the participant sample group by assessing their ability to rank rackets appropriately so as to only include skilled perceivers has also been shown to be a method of improving the quality of data extracted from the test. A few quick and simple ranking tests with players asked to hit with a set of rackets and simply rate them in order to pre-select skilled participants before conducting the full test might improve the protocol. The protocol could be improved further by implementing a wider variable test range which might be possible with moment of inertia with improvements in racket technology and materials reducing the initial racket weight and moment of inertia, and may be easier to achieve for some other variables. This might be particularly important if the sample group tested was chosen from a different demographic. Although the test is not physically demanding and would probably be suitable for players of almost any age or physical development, as has been discussed above, less experienced and less skilled perceivers seem to be less sensitive to changes in racket performance. It is conceivable, however, that any demographic could be filtered to find the more skilled perceivers for the given population, even if they are not as skilled relative to a more experienced sample of players the results should be of the higher quality for that group. A further consideration that might help to improve the quality of the data is the shot selection chosen for testing. Some shots, such as the serve or volley, require greater manoeuvrability to perform the stroke so might make some relevant aspects of racket feel more prominent to the participant.

The research proves that subjective perception can be correlated to experimentally measured objective racket characteristics. The degree of variability, even amongst informed and experienced subjects, means that sufficient confidence in the identified trends can only be established through use of a larger more expert participant group than was possible in the research presented here. Nonetheless, the likelihood that such relationships do in fact exist and can be usefully quantified by this approach using the superior instruments developed has been proven.

9.5. Fatigue Testing

> Do the more play realistic and generally fatiguing experimental protocols enabled by less intrusive instrumentation give rise to significantly different performance excitation scenarios to those produced in unfatigued play

The data collected from the fatigue study was sufficient to address this question although testing had to be terminated before it was fully completed.

Methodology

Unlike the lower values reported by Bowyer (2003) the results of the heart rate and RPE were maximal and showed that the test was capable of taking participants to or near their VO2max and so was successful in achieving this high level of fatigue within the test time frame. This greater level of fatigue was only possible because of the greater freedom allowed by the wireless ‘smart racket’ instrumentation system. Bowyer was only able to use a wired system, and as such was restricted to examining sub maximal local muscular fatigue that could be achieved with minimal participant movement.

Although the protocol was shown to be effective, it may be improved if it were possible to control the ball delivery frequency so that the player travelled the same distance between shots, but the shot frequency increased with each level. This would bring in a new element of control to the test so the player's shot production was influenced less by the distance of movement required to meet the ball in the impact zone. In the current protocol players in the early stages of the test are often standing in the impact zone awaiting the ball delivery; it is only after the early levels that they begin to have to move any substantial distance to meet the ball.

Irrespective of this adjustment, the methodology was shown to be a novel and useful progression of that currently reported in the literature forming a standardised method that allows physical measures to be taken from the player and racket during real play.

Results

Up to 20% higher average peak to peak acceleration values were observed towards the end of the tests in the majority of the 5 complete accelerometer data sets as the participant reached the later stages of fatigue. This finding indicated that, from the tested sample and based on the work reported by Glynn (2007), players were hitting a significantly higher frequency of off centre impacts as they became fatigued ($P<0.05$) and potentially exposed to a higher risk of injury as a result. Given that elite tennis players tend to be more highly conditioned than less experienced players and thus less susceptible to fatigue, this might also explain why the recreational playing population more frequently experiences tennis elbow. This considered, it would be expected that a sample of recreational players would exhibit more extreme results with much higher frequencies of off centre hits and a more dramatic increase with fatigue.

A comparison of racket type showed that significantly higher peak to peak acceleration values ($P<0.05$) were evident when a tour racket, rather than a recreational style racket, was used. The relatively small 2% average difference in the values could be explained by the higher polar moment of inertia of the recreational racket. This quality would also reduce the sensitivity of the racket to off centre impacts which could help explain the smaller increase in the peak to peak values when compared to the tour racket as the player became more fatigued. The player was able to complete an additional level of the test when using the tour racket, which might help to explain the difference in the observed increase in peak to peak acceleration values. Although the data set is insufficient to state with any certainty, further speculation on the results might also conclude that the tour racket was less fatiguing to use than the recreational racket for this player. It is perhaps difficult to conceive why this might be the case until the hitting technique is considered; when a tennis racket is used by experienced players the whole body is utilised to generate power and spin. A racket that makes it more difficult to spin or control the ball for example might require the player to make more extreme adjustments to their stroke technique that could potentially be less efficient and result in an earlier onset of fatigue.

Summary

Ultimately, the demonstration of a generally effective fatigue protocol and the findings in the results analysis showed that significantly different performance excitation scenarios were observed in the given sample compared to those produced in un-fatigued play thus answering the research question and further proving the validity of the original hypothesis.

9.6. Conclusions

The original research hypothesis can be broken into three key parts:

- Improved subjective assessment of tennis racket performance
- Improved objective assessment of tennis racket performance
- Superior racket design evaluation
- Superior fatigue related injury investigation

A useful product of the research was the development of standardised methodologies that could be implemented in a variety of alternative applications.

- Methodology development:
    - Perception test methodology
    - Fatigue test methodology

The work presented in this thesis addresses each of these parts and thus satisfies the research hypothesis as follows:

Improved subjective assessment of tennis racket performance

- The perception relationship model has proved to be a useful tool to be used to guide research, create more informed player questionnaires and aid racket design and as such has improved the subjective assessment of tennis racket performance.
- There is a conceptual model used by players to assess and express their perception of tennis racket performance that can be represented by a perception relationship model.
- The main elements of player perception called general dimensions in the model are ranked in order of importance as shown in the following table reproduced from table 4.2:

Table 4.2 General dimension relative importance values

General Dimension	Relative Importance
Sound	79%
Grip	76%
Power	73%
Control	67%
Feedback	56%
Racket Dimensions	51%
Flexibility	30%

Improved objective assessment of tennis racket performance

- Objective assessment of tennis racket performance has been substantially improved with the development of a non invasive wireless instrumentation and data acquisition system. Its application has been demonstrated and proved effective in a variety of test environments.

- The wireless smart racket instrumentation system makes it possible to take multiple simultaneous measurements of critical performance phenomena without inhibiting prolonged real play use or compromising or biasing a player's perceptions of racket behavior

Superior racket design evaluation

- The perception relationship model has been used as a research guide by Head AG and could be used in a similar way to guide design as is discussed in Chapter 4 (Section 4.7).
- Through the application the newly developed perception protocol, testing has shown that in specific cases for the experimental range, subjective perception data can be correlated to objective physical measures of racket performance. These findings presented in Chapter 7 could be used to assist in guiding the design process.
- Changes in moment of inertia correlate with player perceptions of power, control, balance, weight and flexibility.
- The majority of the players tested were not able to reliably perceive a difference in the changes in moment of inertia presented to them
- A participant sample group of skilled perceivers filtered according to a spearman ranking coefficient of more than |0.6| improves the quality of data collated from perception testing

Superior fatigue related injury investigation

- Both the perception relationship model and the wireless instrumentation system tools have been effectively used to create simulated play protocols to investigate elements of player perception and the effect of fatigue on performance and risk of injury.
- Application of the fatigue protocol also successfully demonstrated that players within the tested sample experienced significantly different performance excitation scenarios to those produced in unfatigued play.
- The wireless instrumentation system enabled the development of a more play realistic protocol that was able to fatigue participants to or close to their VO2max

- Most of the participants tested exhibited higher average peak to peak acceleration values as they reached the later stages of fatigue indicating that they were hitting a higher frequency of off-centre impacts
- Off centre hits are associated with a higher risk of developing tennis elbow (Glynn 2007) so these players were at more risk of injury as they became fatigued
- Fatigue test results indicated that racket design may have some effect on rate of fatigue, although the data set was insufficient to draw any definitive conclusions and this speculation should be treated with caution pending further work

Methodology development

- The perception test protocol contributes a new standardised methodology to investigate the relationship between subjective and objective measures during real play and ultimately could be used to develop further guidelines for racket design.
- The fatigue test methodology was shown to effectively fatigue participants to or near their $VO2_{max}$ in a simulated real play environment. Essentially this is a unique standardised tennis specific methodology that is adaptable for further tennis fatigue related research enabling investigation into numerous aspects of performance, nutrition, racket design or risk of injury for example.

CHAPTER TEN

FURTHER WORK

10.1. Perception relationship model

The version of the perception relationship model presented in this thesis has a number of gaps where no data exists to support parts of the maps structure or lexicon. These gaps exist due to time restrictions placed on the project that necessitated the prioritization of a limited number of areas deemed likely to be of most relevance or importance to the research. Given more time a further postal questionnaire could target these gaps in order to complete the model (map and lexicon). The questionnaire would need little additional development, since the question and website format would remain the same.

The perception relationship model can be used to produce better educated and more informed test questionnaires. By using the appropriate choice of language players' are less likely to misinterpret a questions meaning. Player responses to open questions can also be interpreted using the model to, in effect, translate the players' language. Although the benefit of using a more informed questionnaire has not been compared in a controlled experimental manner to more conventional questionnaires and the results of such a study may prove to be of some interest, it seems that this will not be an entirely necessary process. The test would involve constructing a questionnaire in an uninformed manner and an alternative questionnaire guided by the model, essentially comparing an uninformed format to a well informed educated format, the results of which could probably be predicted.

The techniques and methods developed to create the perception relationship model have been demonstrated with the production of two different feel maps (English and German). These techniques could also be used to develop alternative perception relationship models relevant to other sports contexts important to the industrial partners such as badminton, racket ball, squash or skiing.

10.2. Instrumentation Development

The wireless device made substantial improvements to the area of racket instrumentation but was not completely functional. Refinements to the configuration could address the problems with grip force measurement and the remaining reliability issues. It is suspected that these issues may be caused by interference between the various elements of the wireless device. Further diagnosis would help reveal the source of the problem so that it may be addressed to improve the wireless device performance.

Further improvements could be made by replacing the piezoelectric accelerometers with piezoresistive technology. The smaller piezoresistive accelerometers would allow smaller sensors to be used and enable further refinements to the mount to make it more discrete and to have less influence on the player. These accelerometers would also enable the capture of the lower frequency swing accelerations in addition to the frame vibrations. This would be useful for the investigation of the effect of fatigue on performance where adaptations to stroke technique are of particular interest.

10.3. Perception Testing

The success of the perception test protocol can be built on to investigate a wider range of moments of inertia, and to investigate other elements of the racket such as weight or string tension. The results analysis from the relatively narrow test range of moments of inertia suggested that trends exist that relate this racket characteristic to player perceptions and racket performance. These correlations could be verified with a wider test range that would be expected to reveal clearer and better defined correlations. It might also be expected that new trends would emerge given that this would have more radical effects on racket performance and players would be able to more easily differentiate between the racket configurations. To achieve this, a lighter, lower inertia racket would have to be sourced to allow a greater range without exceeding that which can be found on the current market. Improvements in racket and materials technology would allow the production of these lighter, lower inertia rackets, although it may be necessary to produce a custom designed racket if the market demand were to move towards a heavier racket trend.

The test protocol could also be adapted to be applied to other racket sports such as badminton, racket ball or squash. Some more distinct changes to the protocol could adapt the technique to be suitable for any multitude of other equipment dependent sports such as skiing, snow boarding or hockey.

The production of a perception relationship model relevant to other racket sports would form the base for the adaptations to the test protocol. This would allow an appropriate test questionnaire to be developed and help to prioritise which element of the racket to investigate initially. Adaptations to the location and size of the target grid would be relatively simple to implement, with experienced coaches and players acting as consultants to ensure it mirrored the demands of real play as closely as possible. The ball or shuttle delivery could pose the biggest challenge since although ball launchers are common place in tennis, they are far less common in badminton, squash and racket ball. If badminton is considered it might be possible to source a shuttle launcher alternatively the shuttle could be delivered by means of a standard singles high serve hit by an experienced player or coach since it is common for coaches to hit a 50cm square target accurately and consistently, a comparable performance to that expected from the ball cannon used in the testing presented in this thesis. To help regulate the timing of the feed, although not as suitable as the automated delivery provided by the ball cannon, some form of metronome or other timing device would be a reasonable solution.

10.4. Participant Selection

The results of the perception testing suggested that some participants were more ‘skilled’ at perceiving racket properties than others. A test that refined the participant selection to only include these more skilled perceivers, in much the same way that tea or wine tasters are employed for quality testing of products, in order to attain better quality data. It might be argued that this would be a futile task in as far as commercial racket research is intended, for the main part, to increase a rackets appeal to the general playing population so as to increase the market share of the product, rather than just increasing the appeal to a select proportion of the population more adept at perceiving. However, it could also be argued that skilled perceivers could help to act as an advanced guide to future research with small improvements gradually over time amounting to more substantial changes that are perceivable to a greater proportion of the tennis playing population, rather than attempting to find trends in potentially confused and conflicting data sets..

10.5. Fatigue Testing

The fatigue testing conducted as part of the research was terminated before the full objectives of the study were completed due to a failure in the wireless data acquisition system. The causes of the failure were subsequently addressed to produce a more reliable system. A repeat of the fatigue tests with the revised device would allow the full objectives of the testing to be completed and verify the existence of the emerging trends observed in the original results analysis.

In the course of the research the fatigue test protocol was shown to be effective and could again be adapted to investigate the effects of fatigue on other elements of the racket or other tennis equipment. Further adaptations, similar to those discussed above (section 10.3) could also make the protocol suitable to be applied to other racket sports.

Although heart rate and perceived RPE were taken as indicators of the level of fatigue experienced by the participants, confirmation that fatigue is occurring could be sought by collecting more tangible physiological data. Douglas bag or other more mobile respiratory exchange measuring equipment would be able to show the actual level of VO_2 used by the player at different stages during the test. A simpler and easier method to implement would be a comparative test between the well established multistage fitness test and the fatigue test protocol. Work reported in the literature has shown the multistage fitness test to be a good predictor of VO_2MAX and a comparison of the 2 tests would be a simple way of attempting to correlate the level of fatigue achieved in the tennis test without the need for any additional equipment.

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COSMETICS
appeal
material
familiarity
shape
branding
quality
colour
design trend
FLEXIBILITY
frame firmness
movement
GRIP
adhesion
thickness
condition
age
dimensions
material
length
shape
section shape
relief
firmness
POWER
effort
achievable pace
response
CONTROL
racket
ease
spin
mishit
effect
ball
ANTICIPATED USE
shot type
physically weak
experience
FEEDBACK
familiarity
comfort
ball
racket
quality
vibration
STRING BED
guague
length
size
tension
pattern
type/material
age
wear
SOUND
duration
pitch
quality
volume
appeal
percieved performance
INERTIA PROPERTIES
balance
weight
swing ease
PHYSIOLOGICAL EFFECT
effort
injury
RACKET DIMENSIONS
frame section
width
length
proportions
head

APPENDIX 1 – PARTICPANT INFORMATION FORMS

SPORTS TECHNOLOGY TENNIS RESEARCH

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be deleted/destroyed at my request.

I understand that all the information I provide will be kept for up to 3 years after which time it will be deleted.

I understand that any of the information I provide maybe used anonymously for training purposes.

I agree to participate in this study.

Your name ____

Your signature ____

Signature of investigator ____

Date ____

HEALTH SCREEN FOR STUDY VOLUNTEERS **Name or Number** ....

It is important that volunteers participating in research studies are currently in good health and have had no significant medical problems in the past. This is to ensure (i) their own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:
   - (a) on medication, prescribed or otherwise .... Yes ☐ No ☐
   - (b) attending your general practitioner .... Yes ☐ No ☐
   - (c) on a hospital waiting list .... Yes ☐ No ☐
2. **In the past two years,** have you had any illness which require you to:
   - (a) consult your GP .... Yes ☐ No ☐
   - (b) attend a hospital outpatient department .... Yes ☐ No ☐
   - (c) be admitted to hospital .... Yes ☐ No ☐
3. **Have you ever** had any of the following:
   - (a) Convulsions/epilepsy .... Yes ☐ No ☐
   - (b) Asthma .... Yes ☐ No ☐
   - (c) Eczema .... Yes ☐ No ☐
   - (d) Diabetes .... Yes ☐ No ☐
   - (e) A blood disorder .... Yes ☐ No ☐
   - (f) Head injury .... Yes ☐ No ☐
   - (g) Digestive problems .... Yes ☐ No ☐
   - (h) Heart problems .... Yes ☐ No ☐
   - (i) Problems with bones or joints .... Yes ☐ No ☐
   - (j) Disturbance of balance/coordination .... Yes ☐ No ☐
   - (k) Numbness in hands or feet .... Yes ☐ No ☐
   - (l) Disturbance of vision .... Yes ☐ No ☐
   - (m) Ear / hearing problems .... Yes ☐ No ☐
   - (n) Thyroid problems .... Yes ☐ No ☐
   - (o) Kidney or liver problems .... Yes ☐ No ☐
   - (p) Allergy to nuts .... Yes ☐ No ☐
   - (q) Tennis elbow .... Yes ☐ No ☐
4. **Has any,** otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise? .... Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (eg to confirm problem was/is short-lived, insignificant or well controlled.) ....

Additional questions for female participants

- (a) are your periods normal/regular? .... Yes ☐ No ☐
- (b) are you on "the pill"? .... Yes ☐ No ☐
- (c) could you be pregnant? .... Yes ☐ No ☐
- (d) are you taking hormone replacement therapy (HRT)? Yes ☐ No ☐

Thank you for your cooperation!

Loughborough University 28.5.1999/WJ Clarke

APPENDIX 2 – PARTICIPANT LETTER OF INVITATION

Wolfson School of Manufacturing
and Mechanical Engineering
Loughborough University
Loughborough
Leicestershire
LE11 3TU

Tel: 01509 227681
Email: a.e.statham@lboro.ac.uk

12th February 2003

Dear Sir or Madam,

Loughborough University Sports Technology Group is conducting research into how tennis players perceive and assess their preference for a tennis racket. To support this activity interviews are being conducted with experienced tennis players to establish the language they use to describe the characteristics of and differences between racket models and configurations. The interviews will be conducted, two players at a time, at a suitable tennis facility. Several rackets with a variety of characteristics will be provided for the interviewees to use and their descriptions and assessments of each recorded.

We would like to invite you to be part of this study so that you might share your experience and expertise with us. The interviews will take no more than 1½ hours on-court. During the interview you will be required to hit serves and rallies, as in a typical warm up drill, with around 10 rackets. You will be asked to comment on each in turn.

If you would like to participate then please contact me by telephone, text, email or mail using the contact information above.

Thank you for your time,

Yours Sincerely,

Andrew Statham
Sports Technology Research Group
Wolfson School of Mechanical & Manufacturing Engineering
Loughborough University

APPENDIX 3 – INTERVIEW GUIDE

Interview Guide

Subject number ______________________ Date ___________

Name _________________________________ Age ___________

Section 1

I would like to begin by thanking you for agreeing to participate in this interview study. The purpose of the study is to establish what factors contribute to tennis players' racket preferences. Your involvement is entirely voluntary and during the process of the interview, you are free to decline to answer any questions or to terminate the interview at any time.

I would like to use a tape recorder to get complete and accurate information, and to make the interview process more efficient. The tape recording will be used to make a typed transcript for later scrutiny and reference. Will you consent to the use of this equipment and the subsequent analysis of the recording for the purposes of the study?

There are no right or wrong answers to the questions I will be asking, we merely wish to learn from your experience and expertise. If at anytime you need clarification or wish to ask me any questions feel free to do so.

Section 2

I would like you to have a number of rallies with each racket, when you are ready I want you to explain/describe what factors have influenced your overall impression of each racket.

Discuss:

Flexibility
Strings
Cosmetics
Length
Grip
Sound
Weight
Racket Material
Head Size
Vibration
Brand
Age
Wear
Performance
Length
Balance
MOI

Descriptors used (do they mean good/bad, is it important, how would it be in an ideal racket):

Section 3

Now picture yourself playing an ideal game with the ideal racket. Talk me through the experience including any contributing factors that the racket provides.

Where in the game are their perceptions most intense?

Section 4

Finally I would like to ask you for some feedback about the interview itself

Are there any important factors we have failed to discuss?

Did the recording equipment inhibit or affect you in any way?

Have you any comments or suggestions about the interview itself?

Thank you very much for participating in this interview.

APPENDIX 4 – PERCEPTION TEST INFORMATION SHEET

TEST INFORMATION

Loughborough University Sports Technology Group is conducting research into player perceptions of tennis racket characteristics. As part of this test measurements of acceleration and grip force will be taken by the use of a wireless data logger. Several similar rackets with a variety of characteristics will be used during the tests.

The tests should last no more than two hours on-court. During the tests you will be required to hit 15 cross court forehand ground strokes with a control racket, fed to you by a ball canon. You will then be given one of four test rackets and fed another 15 shots. After this hitting period, an interviewer will ask you some questions about the racket. Data acquired from both the instruments and the questionnaire will be stored for later analysis, and any published results will be reported anonymously.

If you wish to ask any questions or would like to terminate the testing at any time, please speak to any of the researchers present.

APPENDIX 5 – RACKET TEST QUESTIONNAIRE

Racket Test Questionnaire

How did the racket sound?

low pitched | high pitch

'dull'
'dead'
'thud'

'ping'
'ting'
'tinny'

How much power or pace did the racket have?

low | high

'no springiness'
'can't hit hard'
'no power/ pace'

'goes like a rocket'
'ball flew off the racket'
'racket has power/pace'

How much control did the racket have?

low | high

'no control'
'not much touch'
'difficult to time the ball'

'good control'
'real touch'
'good for getting the ball in'

How much vibration was present in the racket have?

low | high

'no vibrations with it'
'no wobbling effect'

'it shakes'
'It shocks you'

How flexible did you find the racket?

flexible		stiff
'lots of movement' *'less solid'* *'flexible racket'*		*'it's hard'* *'like a plank'* *'more solid'* *'really stiff'*

How was the feel/ feed back of the racket?

low		high
'dead racket' *'no feedback'*	*'good sense in head'* *'nice connection'*	*'like hitting a dustbin lid'*

How was the balance of the racket?

Head light	well balanced	head heavy
'handle heavy' *'weight near handle'* *'head light'*	*'balanced racket'*	*'weight in head'* *'head heavy'*

What was the weight of the racket like?

low		high
'low weight' *'light racket'*		*'like swinging a sledge hammer'* *'heavy racket'*

APPENDIX 6 – WEIGHTED LEXICON

Ref	General Dimension	Sub Theme	Vocabulary/ Quotation	Relative Importance %	Relative Importance SD	Relative Importance n	Percentile Use %	Percentile Use SD	Percentile Use n
1	Anticipated Use	Experience	players racket						
			sunday afternoon park play racket						
1	Anticipated Use	Physically Weak	good racket for older people						
			like an inappropriate kids racket						
1	Anticipated Use	Shot Type	(not) good for volleys						
			could(n't) play drop shots with racket						
			felt good for serving						
			good/bad for serves						
			racket for beginners				24	0	50
2	**Control**	Ball Control	difficult to time the ball	**83**	**17**	**49**	75	0	50
			good for getting the ball in				33	0	50

			have to hit out of the middle				4	0	50
			its hard to get spin				27	0	50
			struggle to know where the shots going				37	0	50
			difficult to hit in the middle of strings						
			forgiving racket						
2	**Control**	Mishit/ Ease	hard to find sweet spot	**83**	**17**	**49**	43	1	50
			mishit alot						
			seems like I was hitting a mishit everytime				49	1	50
2	**Control**	Mishit/ Effect	can hit anywhere but middle is best	**83**	**17**	**49**	31	0	50
			In the middle it was nice, but if you hit it outside the middle of the racket it was twangy				65	0	50
			nice in the middle but not off centre						
			off centre hits don't go well				10	0	50

			seems like I was hitting a mishit everytime				33	0	50
			shot dies off centre				49	1	50
			stability						
2	Control	Racket	(un) manouverable racket	**83**	**17**	**49**			
			control racket				24	0	50
			hard to manouver				65	0	50
			quite big for running out wide				24	0	50
			racket does what it wants				63	0	50
			racket means timing is out						
			racket restricted swing				25	0	50
			timing is out						
2	Control	**Spin**	kept catching the frame trying to put spin on the ball	**67**	**26**	**49**	25	0	50

			spin				
2	**Control**		real good for touch	**83 17 49**	51	1	50
			touch/control				
			unforgiving racket				
3	**Control/** Power		power without control	**83 17 49**	27	0	50
4	Cosmetics	Appeal	(not) aesthetically pleasing				
			look of racket is offputting				
			looks horrendous				
			not attractive				
			not keen on racket visually				
4	Cosmetics	Branding	karakal grips				
			only ever play with wilson rackets				

			wilson dampener on head racket				
			wouldn't go for kubler				
4	Cosmetics	Colour	colour				
4	Cosmetics	Design Trend	modern,old racket				
			old fashioned				
			old racket				
			olden days racket so puts you off				
4	Cosmetics	Familiarity	cumbersome shape		39	0	50
			doesn't look like tennis racket				
			egg shaped		18	0	50
			looks like a normal racket				
			looks old fashioned		39	0	50

			looks strange				
			racket has a weird head shape		37	0	50
			racket is a strange shape		41	0	50
			shape makes it feel longer		75	0	50
4	Cosmetics	Fashion	jimmy conners type aluminium look		33	0	50
			looks old fashioned		55	1	50
4	Cosmetics	Material	aluminium racket				
			metal racket				
			plasticy				
			titanium horrible to play with'				
			wooden				
4	Cosmetics	Quality	cheap looking				

4	Cosmetics	Shape	frying pan shape							
			strange/wierd shape							
4	Cosmetics		like a kids/childs racket				16	0	50
			looks like a lego block						
			looks like a snow shoe						
			looks like I'll be able to smack it						
5	**Feedback**	Ball	feel on the ball	**62**	**28**	**49**	55	1	50
			feels like its (not) going in the strings				10	0	50
			felt like hitting a brick				16	0	50
			heavy ball				80	0	50
			heavy ball feels really heavy				80	0	50
			nice connection				20	0	50

			(un)comforatble racket				14	0	50
			(un)comfortable grip				18	0	50
			can get used to it				43	1	50
			Cant get feel on the ball				69	0	50
			comfortablestrings						
5	**Feedback**	Comfort	feel a nice connection	**62**	**28**	**49**	53	1	50
			racket didn't move much				47	1	50
			racket shocks you				2	0	50
			shank the ball				22	0	50
			smooth stroke						
			take back wasn't smooth				45	1	50
5	**Feedback**	Familiarity	alien feel	**62**	**28**	**49**			

			can get used to it				47	1	50
			feels weird				14	0	50
			felt foriegn				8	0	50
			felt like a squash racket						
			first ever racket						
			not familiar with racket				45	1	50
			not used to the racket				27	0	50
			not used to,familiar with racket						
			racket swings smoothly				16	0	50
			similar to own racket				37	0	50
			strange to play with/feels strange				61	0	50
			takes a bit of getting used to				55	1	50

5	**Feedback**	Quality	cheap racket	**62**	**28**	**49**	4	0	24
			thought it might break,snap				4	0	24
			top end racket				4	0	24
			wobbling effect				4	0	24
5	**Feedback**	Racket	(don't want to) hit things with racket	**62**	**28**	**49**			
			dead racket				16	0	50
			good sense in the hand						
			hard racket						
			lively racket						
5	**Feedback**	Vibration	dampner stops vibrations to elbow	**62**	**28**	**49**			
			dunby/dampener						
			Jugga jugga jugga through the arm						

			shakes				4	0	24
			vibration						
			vibration gave tennis elbow						
			vibrations				29	0	50
5	**Feedback**		didn't feel like hitting off the sweet spot	**62**	**28**	**49**			
			feel/feedback						
			lively strings						
			wishy washy						
6	**Flexibility**	Frame Firmness	cricket bat is more solid, dustbin lid less	**56**	**28**	**49**			
			like a plank						
			solid racket/frame						
			solid racket/solid on the ball						

			stiff racket							
			sturdiness behind the ball							
6	**Flexibility**	Movement	racket got a lot of/no movement (flexible)	**56**	**28**	**49**				
			racket was moving							
6	**Flexibility**		(in) flexibility	**56**	**28**	**49**				
7	Grip	**Adhesion**	(not) slippy grip	**74**	**22**	**49**	45	1	50
			can('t) change grip easilly				31	0	50
			cushy grip				61	0	50
7			grip would give me blisters				31	0	50
			sticky grip				65	0	50
			tacky grip						
7	Grip	Condition of Grip	grips wear well				73	0	50

7	Grip	Condition/ Age	old grip				
			prefer grips today		80	0	50
			prefer modern grips				
7	Grip	Dimensions	big/small grip				
			grip size				
			grip width				
			small grip		63	0	24
			tiny grip		25	0	50
7	Grip	Dimensions/ Length	grip too small to fit double handed back hand				
			hold further up the handle				
			long/short grip				
			long/short handle/grip				

			build up grip with overgrips						
7	Grip	Dimensions/ **Thickness**	effect of grip size on tennis elbow	**77**	**24**	**49**			
			grip felt weird for double handed backhand with grip getting bigger at top						
			can feel the wood underneath grip						
			cushion grip						
7	Grip	Firmness	hard/solid grip						
			soft grip						
			solid grip						
7	Grip	Material	leather grip				29	0	50
			grip felt like paper						
7	Grip	**Shape**	grip shape	**51**	**29**	**49**			
7	Grip	Shape/ Relief	ridges on grip						

			smooth grip							
7	Grip		can('t) hold grip tight enough							
			secure grip							
8	Inertia Properties	**Balance**	balanced racket	**76**	**22**	**49**	49	1	50
			feels like you could get injured				41	1	50
			felt like swinging a sledgehammer				27	0	50
			handle heavy				41	1	50
			head heavy				82	0	50
			head heavy gave pain to the wrist				2	0	50
			head light				18	0	50
			light racket				27	0	50
			weight gave it power				6	0	50

8	Inertia Properties	Swing Ease	struggle to get shot shape						
			unwieldy/ungainly						
8	Inertia Properties	**Weight**	heavy racket	**77**	**22**	**49**			
			weight						
			weight puts you off balance						
			wieght of racket affected movement						
9	Physiological Effect	Effort	(not) tiring to play with						
			easy to play with						
			hard work						
			made arm tired						
			racket was hard work				22	0	50
9	Physiological Effect	Injury	felt like elbow would go/tennis elbow racket	**77**	**22**	**49**			

			gives pain to the wrist(head heavy)						
10	**Power**	Achievable Pace	can't hit hard with a shock absorber	**67**	**22**	**49**	2	0	50
			feeble racket				18	0	50
			flies/flew off racket				63	0	50
			goes like a rocket				25	0	50
			no springingness/not much spring				33	0	50
			one pace racket				8	0	50
			pingy/pings off quickly				35	0	50
			popping off				12	0	50
			power/pace				69	0	50
			racket had strength				35	0	50
			racket is real good for touch				51	1	50

			took effort to get power/pace				45	1	50
10	**Power**	Effort	Could give nothing back	**67**	**22**	**49**	65	0	50
			Difficult to generate pace				24	0	50
			Get a lot of power not much effort				18	0	50
			hard work generating power				43	1	50
			It’s a fairly once pace racket				20	0	50
			Its doing too much for me				57	1	50
			lot of effort to generate power				12	0	50
			power with little effort						
			responsivre racket				24	0	50
			too lively				57	1	50
10	Power	Response	does(n't) respond to comming ball speed/could(n't) feed off the pace				16	0	50

			responsive/no response off racket				
			bulky frame		18	0	50
			catch,hit the frame		25	0	50
			chunky frame		65	0	50
			narrow racket		41	1	50
			out of proportion		22	0	50
			thick frame		63	0	50
			thin beam		20	0	50
11	Racket Dimensions	Head	big head		57	1	50
			small head				
			head shape				
			head size	**51 29 51**			

			huge face				
			oversize				
11	Racket Dimensions	Length	racket length, long racket				
11	Racket Dimensions	Proportions	big throat area a bit weird a bit off putting		79	0	24
			big Y arch		58	1	24
			long distance from hand to racket head		54	1	24
			long racket		58	1	24
			no 'heart'				
			size puts you off		54	1	24
11	Racket Dimensions	Width	width of racket		58	1	24
11	Racket Dimensions		beast of a racket		20	0	50
			big racket				

			big size						
			large/huge/massive racket						
12	**Sound**	Appeal	(un)pleasant sound	**40**	**30**	**49**			
			embarrising sound						
			irritating noise						
12	**Sound**	Percieved Performance	can pick up how successfull a shot is by the sound	**40**	**30**	**49**			
			supposed to sound like a massive sweet spot						
			out of control noise						
			sound has bigger effect indoors than out						
			sounded like somthing was wrong with the racket						
			sounds affects/helps perception of shot						
			sounds like it goes				22	0	50

			sounds like youve hit a bad shot						
12	**Sound**	Quality	doesn't sound clean/sweet	**40**	**30**	**49**			
			sounds dead				49	1	50
			sweet,clean sound						
12	**Sound**	Quality/ Duration	bite/crunch sound	**40**	**30**	**49**			
			clear cut sounding ball						
			crsip sound						
			doof sound						
			echoing noise						
			hollow sounding ball/impact						
			pushshu sound						
			solid/compact sound						

			fizz sound before impact				58	1	24
			high pitched sound						
			pingy noise						
			pingy/ping factor						
			plain/dull sound						
12	Sound	Quality/**Pitch**	thud noise	**36**	**29**	**49**	63	0	24
			tingy sound				58	1	24
			tinny racket						
			tinny sound						
			twangy sound						
			wooden sound						
12	Sound	Quality/ **Volume**	didn't make a noise/quiet noise	**31**	**28**	**49**			

			loud sound				
			noisy		58	1	24
12	**Sound**		clumpy sound	**40 30 49**			
			sound				
13	String Bed	Age	old strings				
13	String Bed	Dimensions/ Guague	thick/thin strings				
13	String Bed	Material	sounded like gut string				
13	String Bed	Pattern	close strings				
13	String Bed	Size/ Length	long strings				
13	String Bed	Tension	felt like a trampoline				
			tight/loose strings				
13	String Bed	Wear	string damage,relaxation				

14	Pyschological Effect		mental effect of racket					
			Mentally looks like its going deeper			12	0	50

APPENDIX 7 – FATIGUE TEST INFORMATION SHEET

TEST INFORMATION SHEET

Loughborough University Sports Technology Research Group is conducting research into fatigue and its influence on the player. As part of this research tennis players are needed to take part in fatigue tests. As a participant in the testing you would be asked to run through the following.

After a suitable warm up you will be asked to hit balls for one minute fed through the ball cannon, at a fixed feed rate, towards the back hand corner of the court that is referred to as the impact zone. You will be asked to hit backhand cross court drives towards a target area. This will act as a familiarisation to the test.

After a recovery period you will be requested to hit balls in the same fashion, this time running back and forth along the base line to touch a marker with your foot before playing the ball fed from the ball-cannon into an impact zone.

After each minute that passes the marker will be moved further from the impact zone so you have a greater distance to travel between shots. The test will continue until you fail to hit three of the balls fed from the machine or you decide you want to terminate the test for any reason. **You will not be required to give a reason should you wish to terminate the test.**

After this hitting period, you will be asked a series of questions relating to the test. All data recorded from the testing will be stored for analysis and will be dealt with anonymously during processing and in any resulting publications

If you wish to ask any questions or would like to terminate the testing at any time, please speak to any of the researchers present.

APPENDIX 8 – FEEL MAP