The feasibility of sports grips customisation using rapid manufacturing methodologies

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THE FEASIBILITY OF SPORTS GRIPS CUSTOMISATION USING RAPID MANUFACTURING METHODOLOGIES

By
David F. Barrass

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY AT LOUGHBOROUGH UNIVERSITY Loughborough, UK OCTOBER 2006

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Abstract

In many sports where an implement is used to strike a ball, the grip is typically the sole point of contact between the player and implement. The grip significantly influences how a player wields an implement and is also a means for a player to experience impact forces and vibration. This transmission of force and vibration to the hand can affect a player's control, perception of the equipment, and also expose a player to injury or provoke degeneration of existing maladies. In general, the grip is the least expensive component of an implement. Little development over the previous two decades has been invested on the grip when compared to the vast changes in design, geometry and materials used in the implements which they are attached to.

The development and flexibility of a group of manufacturing processes collectively known as rapid manufacturing have begun to introduce customised products to the mass-market. The main advantage of rapid manufacturing processes is the lack of tooling required, allowing parts to be produced directly from 3D CAD models using an expanding range of polymers and other materials. The integration of rapid manufactured parts into recreational sports equipment has not previously been attempted and is the focus of this work, with tennis selected as the candidate sport.

During initial research the breadth of possible racket handle characteristics for customisation was determined. A series of player tests were conducted using a range of rackets with varying handle configurations. Participants were interviewed using open-ended questions to probe responses to sensations elicited by the use of various racket handles. Transcriptions of the interviews were produced and inductive content analysis of the data was used to organise the emergent data themes hierarchically. From this data a structured relationship model was produced with four general dimensions of feel for the tennis racket handle. The purpose of the model was to identify racket handle characteristics that were of significance to players, the feelings elicited by these characteristics, and the relationships between the characteristics and the vocabulary used by the players. The importance of the individual characteristics was then investigated using an internet-based questionnaire.

Evaluation of the structured relationship model enabled production of several customisable handle concepts. A unique handle design was selected which aimed to influence the vibration experienced by users at impact. The handle design utilised the ability of the selective laser sintering process to produce enclosed features, by arranging arrays of spring elements between the racket handle shaft and handle outer shell. While the design required development of both the handle concept and assembly procedure, refinement of the design was restricted by the limited knowledge of racket vibrational properties influencing player perception.

An experimental study was developed to investigate both the performance of the novel handle concept and the influence of vibration on subjective perceptions of racket performance. Three strokes were investigated: cross-court forehand, serve, and forehand volley with measurement of racket and hand vibration. The results support the development of customised sports equipment through clear subject-specific differences in both vibration measures. Varied subjective appraisal of all the test rackets was also observed. Between the strokes examined, significantly different impact locations and vibration measurements were discovered. Various iterations of the novel handle concept were found to
produce reductions of racket vibration measures and some hand vibration measures versus a standard racket handle.
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Loughborough, UK

October 1, 2006

David Barrass
Publications arising from this work

"An expert is a person who has made all the mistakes that can be made in a very narrow field."

Niels Bohr
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Introduction

Problem identification

A large number of ball sports require the use of an implement to strike the ball. If held by the player, the grip is of significant importance in the quality of the shot played. The impact forces and vibration are transmitted to the player's body through the grip. This can affect the player's perception of the equipment and may also cause injury. Generally, the grip is the least considered and cheapest characteristic of the implement, with design specification typically being based on hand size and traction requirements. Significant design developments have raised the importance of equipment in games such that governing bodies are introducing rules to limit performance. The need for equipment personalisation for player comfort and enjoyment then becomes a significant factor. It is envisaged that customisation will be the next significant advancement in sports equipment, and of recent years, rapid manufacturing technologies have developed to the stage where they can be considered suitable for customisation of sports products. However, significant knowledge is still required to enable this concept to develop. A literature review reveals that there is a lack of knowledge concerning the grip with testimonies written by coaches and ex-professional players. These testimonies lead to contrasting opinions concerning optimal gripping with ambiguous descriptions of the grip force required to be exerted by the player. It is apparent that the mechanics of gripping for sports applications are not completely understood, and those factors that contribute to player comfort or feel have still yet to be defined. A comprehensive study is required to study these factors in order that a grip design specification can be developed, using tennis as the candidate sport for this study.

Rules of tennis

In order to develop methods for improving the design of grips for tennis, it is important to establish the boundaries of what is acceptable. This can be achieved by examining the rules of tennis. The International Tennis Federation (ITF) is the governing body for the game of tennis and is responsible for the rules of the game and equipment, (I.T.F., 2004). In this document, rules regarding the racket are described in Appendix II
Appendix II - the racket

a. The hitting surface of the racket shall be flat and consist of a pattern of crossed strings connected to a frame and alternately interlaced or bonded where they cross. The stringing pattern must be generally uniform and, in particular, not less dense in the centre than in any other area. The racket shall be designed and strung such that the playing characteristics are identical on both faces. The strings shall be free of attached objects and protrusions other than those utilised solely and specifically to limit or prevent wear and tear or vibration. These objects and protrusions must be reasonable in size and placement for such purposes.

b. The frame of the racket shall not exceed 29 inches (73.66 cm) in overall length, including the handle. The frame of the racket shall not exceed 12 inches (31.75 cm) in overall width. The hitting surface shall not exceed 15 inches (39.37 cm) in overall length, and 11 inches (29.21 cm) in overall width.

c. The frame, including the handle, shall be free of attached objects and devices other than those utilised solely and specifically to limit or prevent wear and tear or vibration, or to distribute weight. Any objects and devices must be reasonable in size and placement for such purposes.

d. The frame, including the handle, and the strings, shall 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 deliberately change any physical property which may affect the performance of the racket during the playing of a point. No energy source that in any way changes or affects the playing characteristics of a racket may be built into or attached to a racket.

(Appendix II, Rules of Tennis (I.T.F., 2004))

Research overview

This thesis intends to investigate the potential applicability of rapid manufacturing technologies for the production of custom racket grips. This is achieved by first investigating which factors of the grip and handle influence the player and how these factors influence perception. This information is then used to generate a customisable racket concept. The generated concept is then investigated to
determine whether it satisfies both the needs of a customised grip market and those identified by the investigation into player perception of handle and grip factors.

**Thesis outline**

This thesis is comprised of ten chapters, reporting the methods, results and conclusions of the investigation into customised tennis handles. A general review of the literature relevant to the study is provided in chapter one, with more specific literature included in each respective chapter.

**Chapter one**

This chapter investigates the relevant literature to the general problem encountered by the research hypothesis. The racket anatomy and handle manufacture are discussed as well as studies into the forces and effects of racket-ball impacts in tennis.

**Chapter two**

This chapter examines the emergence of rapid manufacturing technologies from rapid prototyping. The cost of implementation of rapid manufacturing and the applicability of the processes is discussed in this chapter.

**Chapter three**

This chapter examines the processes used to elicit and document perceptions of the grip and handle of a tennis racket, formed from structured interviews with players. Through this process a structured relationship model is generated. The model is used to form a basis for identifying tennis players needs and perceptions when gripping a tennis racket.

**Chapter four**

This chapter describes the process taken to develop a novel handle concept. Examination of the initial concept through to the working prototype was conducted.

**Chapter five**

Research into the human response to hand-transmitted vibration is examined in this chapter. This is featured prior to the testing methodology to explain the approaches used and the justifications behind the test and analysis methods used for the racket study.

**Chapter six**

This chapter features the methodology for the investigation of the performance of the novel racket concept and the determination of vibration characteristics influence on player perception.
Chapter seven

This chapter presents the results of the study documented in the previous chapter. The results are grouped by the type of data measured. The results within each section are separated by stroke. The effect of racket type, stroke type and vibration characteristics are determined in this section.

Chapter eight

This chapter discusses the outcomes of the results section. Apparent areas of further research identified by this thesis or limitations of the current work that require further investigation are discussed.

Chapter nine

This chapter presents the conclusion of the thesis and evaluates the overall conclusions to be drawn from the work conducted.
Chapter 1

Literature review

1.1 The game of tennis

1.1.1 Racket anatomy

A tennis racket consists of a frame and the strings. The frame is composed of a head and handle, joined by the shoulders, throat and shaft. Figure 1.1 illustrates the components of a tennis racket and some of the key terms are explained below, from this point on these racket-specific terms will be used when required.

**Bumperguard**: A piece of material fitted onto the head to protect the frame and strings.

**Butt cap**: The device attached onto the end of the racket handle to provide a tapered shape to the racket; it is usually plastic and stapled into place on the handle.

**Grip wrap**: The grip covers the handle of the racket; also known as grip wrap.

**Grommets**: Individual sleeves inserted into holes in the frame in order to protect the strings. Several grommets may be combined to form a grommet strip.

**Handle/pallet**: The part of the frame where the player holds the racket. The end of the handle is referred to as the butt. A pallet is typically used to refer to a handle that is manufactured separately.
and slid onto the racket shaft. This is opposed to a conventional handle which is PU foam moulded directly onto the handle shaft.

**Head:** The section of the racket where the impact should occur, it incorporates the shoulders and yoke. The edge of the frame that runs around the head is called the rim (not displayed on diagram); the top of the head is called the tip.

**Racket face/string bed:** This area is limited by the inner boundaries of the head, shoulders and throat; is also termed the face, or string bed when strung. The strings contained within the racket are typically main strings (running parallel to the length of the racket) or cross strings (at right angles to the main strings).

**Shaft:** The region of the frame between the throat and the handle; extends through the handle.

**Shoulder:** The region of the frame between the head and throat.

**Throat:** The region of the frame between the shoulder and shaft. This is also known as the heart.

**Yoke:** The part of the frame at the top of the throat (situated between the shoulders). This is also referred to as the bridge.

### 1.1.2 Tennis strokes

There are many different strokes that are used in tennis to create contact between the ball and the racket in an attempt to win a point. These strokes are dependent on the position of the ball with reference to the court, the position of the opposing player and the situation in the game. An analysis of strokes by Downey (1970), Douglas (1992) and consultation with senior Lawn Tennis Association (LTA) coaches has enabled a schematic representation of the main strokes that occur in a game of tennis. Strokes that were considered to be particularly rare or specific to a certain individual's games were not included or were encompassed in wider descriptions of the type of stroke. The resulting stroke relationship diagram can be seen in Figure 1.2.

The identification of strokes that occur in tennis is important so that knowledge can be developed about the mechanics of each stroke in order for test protocols to be devised. Elliott *et al.* (1997) had shown that the method of holding the racket may not influence all the biomechanical aspects of forehand groundstrokes, but they do significantly affect several important aspects of stroke technique. Elliot & Marsh (1989) demonstrated that there are significant differences between the preparation for impact and impact conditions for topspin and backspin forehand approach shots. In addition to the definition of the strokes used in tennis, it is useful to determine the frequency of occurrence of each shot in the game of tennis. This knowledge would help to prioritise the importance of the handle's performance for each shot; for example it can be argued that a shot that may occur less than 5% of the time is low in terms of priority to develop an improvement in the shot played than a shot that may occur 30% of the time. There exists published literature analysing the game of tennis, but it
mainly concerns strategy. Hughes & Clark (1995) examined the surface type on elite tennis strategy and O’Donoghue & Ingram (2001) examined the effect of the surface at the four tennis major events on the strategy employed by elite players. O’Donoghue & Liddle (1998) examined the point profiles related to the surface that the players were using. Hughes & Clark (1995) identified the need for further investigation of elite tennis strategy for both males and females on different court surfaces and at differing ability levels. Vergauwen et al. (1998) performed similar investigations and noted that longer rallies occur on clay, resulting in prolonged matches that induce fatigue, increasing error rates and reducing stroke velocity. It may be that appropriate construction of handles could help to offset this fatigue. O’Donoghue & Ingram (2001) identified shots which won the most points. The importance of specific shots need also be identified as solely investigating the frequency of occurrence may lead to a misrepresentation of the importance to a player’s overall game. Unfortunately, as may have been expected, this research also identified some differences in strategy employed by the players on different court surfaces; as there exists significant differences in the percentages of points, where the server approached the net first and the percentage of baseline rallies. It was also shown that there was no significant difference between the percentage of shots won at the net or won from the baseline by the serving player or the receiving player. Additionally, it was apparent that the women’s game was very different to that of the men’s game as the rallies in women’s singles were longer and a greater proportion were played from the baseline. These differences in strategy will more than likely create different shot profiles and occurrences between matches on different surfaces and matches between the different sexes. This suggests that rackets designed specifically for the demands of a person’s game or surface may be useful and that handles may help reduce arm fatigue, injury and even improve players performance. Bloom & Bradley (2003) and Petkovic et al. (2004) have both developed systems that can analyse digital video to recognise the strokes played, although they can currently only manage the recognition of six strokes. They indicate that these systems may be developed to increase speed and accuracy of analysis and Petkovic suggests that future developments in these systems may allow the retrospective analysis of game footage.
Figure 1.2: Diagram illustrating the main strokes used in a game of tennis
1.1.3 Racket gripping

There are 11 basic acknowledged grips in tennis, which are variations on three styles that have developed over the years: eastern, continental and western. The eastern and western were first developed on the east and west coasts of America to suit the contrasting court styles of the two areas. The continental grip and its variations originated in Britain but is typically seen as a European or Australian technique.

Grip choice can have an effect on technique and shot performance. Elliot & Marsh (1989) showed that players executing forehands using an eastern grip produced higher velocities of flexion/abduction of the upper arm during racket motion, but western grip players used ulnar flexion of the hand to create a greater velocity than eastern grip subjects. Further studies noted that by changing the method of holding the racket the ball was impacted forward of the front ankle irrespective of the height of impact (Elliot & Christmass, 1995). Elliot also noted that the western grip gave a lower magnitude of peak racket-shoulder speed compared to the eastern grip. Adjustments in technique for backspin backhands for high and low bouncing balls, irrespective of how the racket is held, were also observed. It appears the choice of grip adopted by players may be attributed to the surface they play on, the type of shot and their own physical limitations.

Racket handles generally consist of eight bevelled faces. The bevels are used to locate the hand by positioning fingers and thumbs. Figure 1.3 illustrates how the handle is defined to allow players to determine where to place their hands.

Figure 1.3: Layout of racket handle geometry used for finding grips (Levey, 2005)
1.1.4 Overview of tennis racket industry

Rackets on average comprise 2.2% of the sports goods sold in the four major European countries (G.B., France, Germany, Spain). The biggest percentage share (3%) of rackets sold occurs in G.B. but the highest ranking sales percentages occurs Spain, where they are the 6th highest selling sporting good (Mintel, 2003a).

Racket sports have grown in popularity between 2001–2003, with 3% of survey respondents having purchased rackets in 2003, an annual growth of 0.7% (Mintel, 2003b). A report examining 2002 tennis equipment purchasing trends, showed that approximately half of tennis consumers bought tennis balls and just over 20% bought tennis rackets and almost 30% bought tennis clothes (L.T.A., 2004). These purchases occurred mainly at specialist sports shops (73%), department stores (9%) and tennis clubs (9%).

Participation trends

Just over 30% of tennis participants are classified as regular participants, whereas squash (50%) and badminton (35%) have slightly more regular participants. The members of squash and tennis clubs are predominantly male (Mintel, 2003c). For the four major European nations, tennis was the most widely participated of the racket sports (18th amongst all sports G.B., 16th in France and Spain, and 10th in Germany (Mintel, 2003a).

A study examining only racket sports found tennis was the most popular of the racket sports, with 13% of UK adults playing to some extent during 2003 and 0.8 million people playing tennis at least 25 times a year (L.T.A., 2004). Just over 10% of respondents participated in badminton and only 6% participated in squash (Mintel, 2003c). For regular play (once a month or more) both tennis and badminton are played regularly by 4% of adults and squash is played regularly by 3% of adults. This may suggest that tennis is more accessible to the casual player, but would not appear to be a barrier to those interested in regular participation in the other racket sports. Only tennis has shown relative consistency in participation levels with both badminton and squash showing a decline in participation levels.

Regular tennis participants comprise two thirds men to one third women. Both tennis and badminton display a similar age profile with participation peaks in the 15-19 age group and 25-34 year age group and a decline in the 20-24 year age group. Tennis players are generally more likely than the population as a whole to participate in other sports, with tennis players playing an average of 3.6 other sports (L.T.A., 2004). Approximately one in four badminton players also play tennis regularly, while 16% of tennis players also play badminton (Mintel, 2003c).
1.2 Current manufacture and customisation

1.2.1 Handle manufacture

Although wood and cork have been used in the past, there currently exist two main methods for producing racket handles: PU foam injection and pallet moulding.

**PU foam injection**

![Image of PU foam handle moulding process](image)

Figure 1.4: The PU foam handle moulding process: a) place racket frame in mould; b) fill mould with PU foam; c) close and heat mould to form handle

PU foam injection is the most popular method for attaching a handle to the racket frame. The attachment of the handle occurs once the racket frame has been produced and cleaned. The frames are placed into open handle moulds, corresponding to the handle geometry and size. The moulds are heated to ensure a good and fast cure of the PU foam once injected into the mould and a silicon agent is sprayed into the mould to ensure easy removal of the handle. Figure 1.4 shows the process of moulding the handle. An operator is responsible for filling the moulds with PU foam using an injection nozzle. Once the bottom half of the mould cavity is filled with the required amount of PU solution another operator closes the top half on the mould around the handle. As these moulds are heated, the PU foam solution expands to fill the shape defined by the moulds. The foam cures from the outside of the mould towards the racket shaft at the centre of mould. The approximate cure time of the PU foam is 2 minutes. Once cured the moulds are opened and the handles removed and the flash cut away (Figure 1.5). These handles are then finished by attaching a buttcap and applying the grip wrap. One alternative method some brands use is to form separate PU foam handles, which can then be glued onto the handle shaft to form the completed handle. The advantage of this process is that the handle does not need to be attached to the racket frame at the factory. Handle sizes can then be applied to rackets according to inventory requirements as long as there is sufficient supply of the handle parts.

**Handle pallet moulding**

The handle pallet is an alternative method of mounting a handle to the racket. This is another process that does need to be performed at the same place of manufacture as the racket frames. This
Figure 1.5: A PU foam handle once removed from mould, shown with flash being removed

Figure 1.6: Example of pallet patent concept ((David & Monty, 2002)

has advantages from an inventory perspective, as a racket can be made only when required. The first idea for handle pallets was produced by Nolan (1991), with a similar concept later developed by David & Monty (2002). The pallet is typically produced by injection moulding. Some manufacturers may use rubber-like polymers as these are believed to provide vibration damping properties to the pallet. The pallet is attached to the racket handle by sliding the flexible pallet around the solid shaft of the racket frame and using adhesive or metal pins to hold the pallet in place. An example of a pallet type handle is shown in Figure 1.7.

Figure 1.7: Example of pallet type handle
1.2.2 Methods of customisation

There already exist mechanisms for the customisation of sports equipment. Most of these have developed through player's experience or equipment specialists modifying equipment to allow improved performance, comfort, or equipment efficiency. This section will examine some of the processes used to adjust the grip and handle to individual's requirements.

Tennis

The methods for sizing the handle for tennis players is less formalised than the procedure used for sports such as golf. It is typically recommended that the handle for tennis players should be as large as can be comfortably held, but it is believed that handles too small or too large can lead to arm injuries and errors in stroke production (Stinger's Assistant, 2000). This section will look at two conventional methods for fitting tennis grips.

Method one Recommends that the most suitable way to select a handle for a player is to size up the handle until the player feels that the grip is too big, and then back the handle down one size. It is suggested that a proper handle size should maintain a 'one finger spread' between the palm and fingers when gripped (Figure 1.8). Table 1.1 shows the standard range of handle sizes for tennis rackets. The origin of this method is not known.
Method two The alternative sizing method is to measure from the tip of the ring finger to the bottom of the lateral crease on the palm of the hand (Figure 1.9). This measurement represents a handle size, as presented as a handle size and circumference in inches. If there is any doubt over the best size for the player, it is typically recommended a smaller size is selected. This is because it is easier to size up a handle than to reduce a handle. The application of additional grip wrap usually adds some size to the handle as well.

Handle Modifications

Handles can be modified in size by using heat shrink tubing. When placed over a stripped handle, the tubing is shrunk onto the handle, increasing it by one size (+3 mm to perimeter). Handles can also be decreased in size. However this is much more difficult and generally not recommended. If necessary the most common way to do this is to shave the handle down slightly. This method is only possible with foam-injected handles. Some elite players have been observed to ‘build up’ the sides or bevels of their rackets using suitable tape. This is different to sizing up a handle. Although it changes the handle circumference, it does not do so in a uniform manner and may actually change the shape of the handle. Players may feel the need to reshape their handle if they have changed racket brand but prefer the geometry of their previous brand’s handle. This becomes necessary because although racket manufacturers tend to use the same shape in terms of number of sides (an octagonal shape) all manufacturers each use different geometries that create handle profiles unique to their brand. However, they use the same handle size guides, see Table 1.1, where the dimensions refer to the acceptable range.
of the handle perimeter. This means that in some cases the transition between one manufacturer to another can be very noticeable. Head is an example of a classic unique profiled handle shape as the dimensions used are also noted for creating an oval shape to their handles, whereas Wilson use a very uniform octagonal shape. The butt cap is also modified by some players; as players who tend to suffer racket slippage when playing may use tape to add bulk to the butt cap to ensure that the racket remains in place in the hand.

Table 1.1: Standard racket handle sizes (Standardization, 1995)

<table>
<thead>
<tr>
<th>Standard handle size</th>
<th>Grips size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>94 &lt; s ≤ 97</td>
</tr>
<tr>
<td>00</td>
<td>97 &lt; s ≤ 100</td>
</tr>
<tr>
<td>0</td>
<td>100 &lt; s ≤ 103</td>
</tr>
<tr>
<td>1</td>
<td>103 &lt; s ≤ 106</td>
</tr>
<tr>
<td>2</td>
<td>106 &lt; s ≤ 110</td>
</tr>
<tr>
<td>3</td>
<td>110 &lt; s ≤ 113</td>
</tr>
<tr>
<td>4</td>
<td>113 &lt; s ≤ 116</td>
</tr>
<tr>
<td>5</td>
<td>116 &lt; s ≤ 119</td>
</tr>
<tr>
<td>6</td>
<td>119 &lt; s ≤ 122</td>
</tr>
<tr>
<td>7</td>
<td>122 &lt; s ≤ 125</td>
</tr>
</tbody>
</table>

1.3 Forces of tennis impact

1.3.1 The impact

According to Brody et al. (2002) a racket experiences a force upon impact. Stiff rackets experience a high force for a short time and less stiff racquets feel reduced forces for a longer period of time. The force of impact causes the racket to vibrate and the racket will continue to do this until the energy is dissipated. Stiffer frames have a higher frequency of vibration than flexible frames since they store less energy. This means that within a given time the stiffer frames experience more cycles of oscillation, with each cycle dissipating some of the vibrational energy. These vibrations can take at least one second for all the frame oscillations to die out with freely suspended, undamped frames.

Several researchers report the contact times between the ball and the racket of 4-5 ms (Cross, 1999; Engel, 1995; Hatze, 1976; Maeda & Okauchi, 2002). Hatze (1976) also identified that subsequent racket oscillations from impact last at least 40 ms.

The force on the racquet from impact causes three things to occur

- The racquet recoils
- The racquet rotates
- The racquet bends
It is these three motions that contribute to the shock and vibration experienced by the player. The recoil and bending deflect the player's hand and the rotation twists it. The head of the racket experiences this impact before anything can be sensed at the handle. Cross (1999) states that the impulse from the impact takes about 2.5 ms to reach the hand, where it is reflected and arrives back at the impact location after the ball is about to leave contact with the racket. The handle motion is strongly affected by the impulsive force exerted by the hand during the collision. This shock at the hand, however, has almost no effect on the ball. This is because for most typical rackets the vibration of the racket from the ball impact must travel to the handle and back to the ball before it leaves the strings if it is to affect the ball. With typical racket vibration frequencies there is little chance of this vibration completing a cycle before the ball leaves the string bed. For rackets clamped at the handle this is not the case. Cross (1999) stated that "Clamped beams and rackets exhibit a 'slingshot' effect where the reflected pulse is able to catch up with the ball before it leaves the racket". This is not typical of a hand-held racket impact as the hand and wrist act more like a pivot joint than a rigid clamp. When this pulse reaches the ball it causes a reduction in contact time by moving the racket away from the ball. Even with the stiffest racquets, it takes 2.5 ms for the bending wave to get to the hand. Any rotation reaches the hand at about the same time. The energy that informs the hand that the racket is rotating and recoiling, is essentially carried by the bending wave. This explains why vibration traces of impacts measured at the handle show a large initial spike. This spike is a combination of translational, rotation and vibrational acceleration. The hand then resists and stops the translation and rotation but the vibration continues and is solely responsible for the rest of the remaining trace.

Hatze (1976) demonstrated that it is not possible for the player to counter the linear and angular impulse reactions that occur at their hands from impact. With an average relative velocity of 35 m·s⁻¹ between the racket and ball, the impulsive moment occurring at the hand would be 482 Nm, about 16 times the value a human hand accommodates under static conditions. Hatze suggests that claims made by players that they can 'guide' or 'control' the ball through impact are incorrect. However, there may be other sensory preceptors that contribute to this perception by the players.

In a laboratory, it is difficult to construct a model of the human hand holding a racket to get reliable, reproducible data on the interaction of a tennis ball with a racket (Brody, 1987). Researchers have used numerous grip situations from rigidly clamped to freely suspended (Baker & Putnam, 1979; Brody, 1989; Elliott et al., 1982; Hatze, 1976). Brody (1987) reported that a hand held racket displays vibrational modes similar to those of a free racket. When a racket is rigidly clamped, its lowest frequency of oscillation is about 25-40 Hz while free rackets have a natural frequency of about 125-200Hz (Brody, 1981). When struck away from node, the hand held racket oscillates at a frequency very close to the frequency of the free racket. There was no sign of the low frequency vibration that
characterises the clamped handle. (Brody, 1987) suggests that because tennis racket frames are stiff, the soft human hand hardly influences them. The annoying vibrations of a tennis racket are believed to be caused by the first harmonic mode of oscillation (Brody, 1981, 1987) which he claimed ranged from 120 - 200 Hz. (Cross, 1999) found that the fundamental frequency of a typical graphite/epoxy composite racket when suspended freely by a length of string is about 125 Hz (time period of 8 ms). This theory is reinforced by Segesser (1985) who suggested that oscillations ranging from 80-200 Hz likely cause the development of tennis elbow. Figure 1.10 shows the shape of the first bending (harmonic) modes of the racket and the node locations in two different grip conditions. If the opinions of researchers such as Segesser (1985) are correct then it is important for measures to be used to minimise the effect of these potentially harmful vibrations.

Hatze (1992) defined a racket’s ‘sweet spot’ as the nodal point of the fundamental transverse vibration mode, the impact location that produces the minimal vibration in the player’s hand. Based on several studies it can be found at some point along the centreline of the strings from the handle to the racket tip (Brody et al., 2002; Maeda & Okauchi, 2002). Nodes are locations where if impacted the racket will not vibrate. If players grip at nodes then they will feel no vibration upon impact. Brody et al. (2002) investigated the relationship between the impact location and level of vibration and discovered that the relationship is not linear and is more likely to be modelled by a curve with a deflection corresponding to the node of the fundamental racket mode. Figure 1.11 shows this trend for x-axis measures of four different freely-suspended rackets impacted at varying points along the stringbed versus vibration amplitude measurement.

Typical testing that has examined the vibration signals of an impacted tennis racket do not consider any vibrations above 1 kHz, as these are typically of small magnitude and are generally caused by the motion of the racket strings. An example of this is the configuration used by Hennig et al. (1992)
to electronically process his acceleration signals, where a 400-Hz low-pass filter was used to remove string vibration signals. A 15-Hz high-pass filter served to eliminate the low frequency components of the acceleration signal due to arm movements during the impact.

1.3.2 Energy dissipation

The transfer of energy from impact with the racket frame is of considerable interest to many tennis science researchers. Normally the hand gripping the racket dissipates the energy associated with the vibration of the racquet when impacted. This is due to the fact that the vibration passes into the arm via the contact made by the hand at the grip. Although it is claimed by Hatze (1976) and supported by evidence from other studies (Brody, 1989) and Elliott et al. (1982), that the hand is the best method of dissipating the vibration of the racquet from impact, there are several other ways in which the energy dissipation can be influenced.

Grip

Surprisingly, there is little scientific information regarding racket grips and the assessment of their effects. Hatze (1992) examined the beneficial effects of grip wraps with regards to vibration and resistance to slip and found that cushioned grip wraps reduced impact shock on vibration transfer on a tennis racket. An integrative vibration transfer index ($\gamma$), and normalised vibration transfer value ($\phi$), were used to measure the effectiveness of the various grip wraps. He found that the results varied by brand and the largest normalised vibration transfer value was 8.85%. In this work he was also able to determine that grip wraps producing a vibration dampening index value of greater than 0.5
were vibration absorbing. However, the method used by Hatze used an artificial arm “replicating the structure and all the important properties of the real human arm”. He remarked that there was “no clear indication whether these reductions are...biologically relevant”. There are also concerns over the complexity of his approach, which could prevent it from being a suitable method for evaluating racket handle or grip wrap damping properties.

**Racket Construction**

The damping of vibrations in most tennis racket frames will only change their playing characteristics slightly, because the hand holding the racket damps out the oscillations in about 20-30 ms (Brody, 1989). Frame materials take about 180-750ms, depending on the racket, to damp the amplitude of oscillation to half the initial value, otherwise known as the damping time. For a racket to internally damp out a substantial fraction of its vibrational energy when hand-held, its 'free' damping time must be comparable to the time measured for hand-held rackets. This is about 2–3 oscillations, not 20 or more cycles as measured for a freely suspended racket. Therefore the racket must contain enough damping material to absorb the energy of the oscillations quickly. Vibrations in tennis rackets have been tested with and without strings. Cross (2001) discovered that when a tennis racket is strung, the fundamental vibration frequency decreases by approximately 10% depending on the string tension and the stiffness of the frame. The mass of the strings (approx 15g) would account for 2% of the frequency drop. He concluded that if an external force is applied to bend the frame perpendicular to its main axis, then the strings parallel to this axis are shortened and the tension drops. The main effect of the strings is that they assist the force because as the frame bends, the string tension develops a component perpendicular to the axis. This component enhances the displacement resulting in a larger displacement of the frame. As a result the frame of the racket becomes softer rather than stiffer and therefore the vibration frequency of the frame decreases.

**Vibration devices**

Vibration dampeners are typically found in the form of small elastomeric devices that can be attached to the string bed near the throat of the racket. The aim of these devices is to reduce vibrations of the racket. In some cases they claim to reduce vibration and discomfort in the hand and arm. These devices are quite popular amongst the tennis playing community with both elite and recreational level players frequently using them.

There is, however, some disagreement about the effectiveness of these devices amongst the research community. Tomosue et al. (1994) showed that the damping material of these devices reduced the amplitude of oscillations at the racket handle and wrist joint, because the vibration dampener appreciably reduced the string vibrations. This in turn had an apparent effect on the frame vibrations. Brody (1989) conceded that whilst both commercially available and homemade dampers eliminated
string vibration quickly and effectively; he pointed out that the damper mass is only significant when compared to the mass of the strings (approximately 15g), but that this is not the case when compared to the mass of the frame (approximately 200-300g). With this in mind, Brody doesn't believe that the string dampers can absorb a significant amount of the frame vibration energy.

Brody showed that racket frames typically have fundamental frequencies between 100 and 200 Hz, whereas strings vibrate at higher, often audible frequencies. Reynolds et al. (1977a) found that annoyance owing to vibration applied to the hand decreases as frequencies exceed 180 Hz. This suggests that discomfort during tennis racket impacts is caused by frame vibration rather than by higher-frequency, lower-intensity string vibration.

Stroede et al. (1999) suggested that it was plausible for vibration dampers to reduce the auditory rather than hand and arm discomfort, since it had been frequently shown that dampers do eliminate the audible 'ping' produced by vibrating strings. Players may associate sound reduction with a reduction in hand and arm comfort, in other words they may experience sensory confusion. Stroede further strengthened her suggestions with tests that showed that when deprived of auditory sensations, subjects did not exhibit any change in impact discomfort between an impact of a racket with a damper attached to the string bed and the same racket without the damper. During these tests, a curtain to ensure the players had no knowledge of whether there was a damper present separated the subjects and the racket. Stroede also demonstrated that accelerometers attached to the racket frame, that the dampers did not affect the frame vibrations, although it was noted that they did influence string vibrations. The only significant effect on impact discomfort that Stroede observed during her test was that the location of impact gave rise to significant changes in discomfort effects. A similar study by Li et al. (2003) concurred with these results as they found that string dampers had no effect on the duration or amplitude of vibration at the elbow, the duration of EMG muscle activity was also not affected for either muscle studied (flexor carpi radialis and extensor digitorum communis) at the elbow. Additionally, Li also examined the perception of comfort and found that the dampers had no significant effect. As Stroede had done previously, Li found that the impact location influenced the duration and magnitude of the vibration at the elbow and in turn influenced the perceived comfort of impact.

Grip Technique

Brody (1989) showed several aspects of vibration dampening that can be influenced by grip technique. The damping times of the rackets when gripped as opposed to freely suspended were significantly shorter (Figure 1.12a). The time needed to damp the oscillations was strongly dependent on how tightly the racket was gripped and where the grip force was applied (Figure 1.12b and Figure 1.12c). Brody also stated that inexperienced players tend to grip the racket with increased tension at the
moment of impact, reducing the magnitude of racket vibration. As a consequence of the increased union between racket and hand, the vibration experienced by these subjects is increased as most of the oscillation energy has to pass into the hand to dampen the racket vibrations. Knudson (1991) noted that the more skilled subjects exerted a greater force on the thenar eminence (of the hand) in preparation for impact than less skilled players. He also noted that force values for advanced subjects at the point of impact were twice that of the intermediate subjects. Hatze (1976) believes that with regards to the tightness of the grip during and after impact a preference must be given to one of two criteria. The reduction of the unpleasant vibrational shocks transmitted to the player’s hand, or the increased power of the tennis stroke.

Figure 1.12: Figures showing racket measurements under varying clamp conditions (Brody, 1989)

A tight grip has been shown to increase the impulsive force and therefore power, but increases the vibrations transmitted to the hand (Elliott et al., 1982; Hatze, 1976; Plagenhoef, 1970). Loose grips can reduce both these effects. Hatze believes that the most advantageous grip pressure is dependent on the skill level of the player, with light to moderate gripping pressures for unskilled players and tight grips for the more proficient players.
The force of the grip

The role of the force or pressure applied at the handle is a controversial subject in tennis. There is substantial disagreement between researchers about the importance of the pressure applied by the player and its effect. As previously mentioned, many studies all report that a tighter grip results in higher ball rebound velocities (Elliott et al., 1982; Hatze, 1976; Plagenhoef, 1970). Other researchers have claimed that the ball rebound velocity is independent of the grip firmness (Baker & Putnam, 1979; Grabiner et al., 1983; Liu, 1983; Missavage et al., 1984; Watanabe et al., 1979). Engel (1995) found, using a rig to simulate properties of the hand, that by increasing the firmness of grip, higher values of peak reaction force, torque and linear and angular impulsive reactions occurred. The typical increases that could be expected from going from high to low gripping force were 10% of peak torque reaction, 20% peak force reaction, 40% linear impulse and 50% angular impulse. Hatze (1976) had proposed that a reduction of grip tightness during and just after impact was one method to reduce the unpleasant vibration occurring at the hand during and after impact. However, this could lead to a loss of 10-15% of the magnitude of the impulse of the stroke. Several researchers have noted that when observing highly-skilled players freely playing strokes, rackets were held very tight but the acceleration of the racket prior to impact was nearly zero (Brody, 1989; Hatze, 1976). Bernhange et al. (1974) and Engel (1995) both observed that more advanced tennis players use shorter durations of maximum grip pressure. Elliott et al. (1982) agrees that the effects of a tight grip are especially significant with off-centre impacts, but supported work by Watanabe et al. (1979) and Baker & Putnam (1979) indicates that the rebound coefficient of the racket and ball is independent of grip pressure for central impacts. There also exists different force profile for different shots. Data taken by Knudson (1991) suggests that the pattern of force loading in the backhand is different from the forehand. Knudson & White (1989) suggested that the hypothenar forces are the critical gripping forces for the forehand. It is arguable that these locations apply any significant force at all. The force is applied by the fingers and thumb and have simply measured at these locations. Knudson's backhand research suggested that the thenar force prior to impact is the primary gripping force in the one-handed backhand. The observed pattern of the hypothenar force prior to impact was very similar to the force created by the base of the index finger in previous research on the forehand (Knudson & White, 1989). In the forehand drive the hand is placed directly behind the handle of the racket and the impact force is more in line with the axis of the arm. Therefore the hand experiences large peak forces (Knudson & White, 1989). With the one-handed eastern backhand grip, the hand is placed on top of the racket handle where the force of impact is more eccentric to the arm and wrist axes.
Ball speeds

To establish an estimate of the forces involved in impacts and aid in the development of suitable theoretical models, typical ball speeds in tennis are documented. A detailed protocol conducted a digital analysis of three different Pete Sampras matches from the 1997 and 1998 Sybase Open, USA (Pallis, 2004). The speed data produced by the digitising system was found to correspond closely with the radar gun readings for the serves, with an analysis of 23 serves that obtained radar gun readings showing an accuracy of about 3.5% with the software calculated values. The advantage of the digitising system was that it allowed the calculation of the speed of the ball at several points during flight, whereas the radar gun is only designed to take the initial speed of the serve. Analysing the speeds of Sampras shots at various stages showed that typically shots lost approximately 30% of the speed pre-bounce and 20% of the initial speed post-bounce, giving a total loss of 50% of initial speed after the bounce. Moreover, before the opponent strikes the ball, another 10% of the initial velocity is typically lost. Therefore by the time an opponent prepares to return a ground stroke the ball will have only 40% of its initial velocity remaining. Table 1.2 summarises the average speeds at the various stages of the shots played by Pete Sampras in his three recorded matches.

Table 1.2: Speeds of Pete Sampras shots at their various stages (Pallis, 2004)

<table>
<thead>
<tr>
<th>Shot</th>
<th>Speed before racket impact (mph)</th>
<th>Max speed after impact (mph)</th>
<th>Pre-Bounce speed (mph)</th>
<th>Post Bounce speed (mph)</th>
<th>Speed before opponent impact (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serve</td>
<td>—</td>
<td>120</td>
<td>87</td>
<td>62</td>
<td>54</td>
</tr>
<tr>
<td>Forehand Return</td>
<td>60</td>
<td>65</td>
<td>40</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>Backhand Return</td>
<td>48</td>
<td>65</td>
<td>40</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>Forehand</td>
<td>19</td>
<td>76</td>
<td>49</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>Backhand</td>
<td>17</td>
<td>69</td>
<td>49</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>Forehand Volley</td>
<td>38</td>
<td>47</td>
<td>31</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>Backhand Volley</td>
<td>42</td>
<td>44</td>
<td>34</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>Overhead Volley</td>
<td>25</td>
<td>110</td>
<td>89</td>
<td>62</td>
<td>54</td>
</tr>
</tbody>
</table>

Although this data is only generated from the shots played by one player (Pete Sampras), it can be assumed that his shots will be very close to the peak speeds that can be observed on the professional tour. From these speeds it is possible to develop theoretical models on the forces involved in racket impacts. These models are important for use in the design and testing of new rackets since there is limited information concerning actual measured forces of impact in professional play. Due to the difficulty of instrumenting a racket without it affecting the racket characteristics and the availability of top professional players willing to participate in tests. Non-invasive methods such as analysis of video footage is the most common way to collect data on the 'elite' players.

One method that has been used to determine the forces imposed by a tennis ball on a surface is the use of ball cannons and force plates. This arrangement does not perfectly replicate the impact of the ball on the string bed, however, it does allow ease of measurement. Figure 1.13 shows the results produced from normal ball impacts with a force plate at various ball speeds.
An analysis of the ball speed values prior to impact from Table 1.2, indicates that there will be many impact values above the $40 \text{ m/s}^{-1}$ mark, for groundstrokes at least. This provides an indication as to reasonable force values that can be expected to be imparted on a racket during play conditions.

### 1.4 Tennis injury

Priest et al. (1980a) investigated 2,684 tennis players with and without elbow pain using a questionnaire to probe potential influences on their injury. They found of all the tennis injuries that the elbow was the most commonly injured joint with 31% of respondents. The ankle and shoulder were the next most common injury sites with 8.0% and 5.2% respectively, followed by knee (4.0%), wrist (2.1%) and forearm (1.1%). Shoulder and knee injuries were more common in men and forearm and wrist injuries more common with women. The fact that injuries to the elbow were almost four times as great as the next most injured region (ankle, 8%) suggests that there is a need to address the prevention of elbow injuries. Of those experiencing elbow injuries, Priest and Braden found that 75% located this pain over the lateral epicondyle. Lateral epicondylitis is found to affect 40-50% of recreational players and medial epicondylitis about 10% (Nirschl, 1974; Roetert et al., 1995). Lateral epicondylitis has received the most attention, as it occurs most frequently and is chronic in nature. Lateral epicondylitis is a very common condition found in the recreational tennis player and is more commonly known as "tennis elbow". The prevalence of tennis elbow is well reported and is perceived to be the greatest hazard facing recreational tennis players (Engel, 1995; Priest et al., 1980a; Roetert et al., 1995). Tennis elbow (TE) is an umbrella term that describes elbow pain localised on the inside or outside of the elbow from a variety of repetitive motions such as writing or shaking hands (Cooke et al., 2002; McLaughlin
It should be noted that only 5% of lateral epicondylitis sufferers are tennis players (Hennig et al., 1992; Pluim, 2000; Renstrom, 1994; Snijders et al., 1987), although 93% of tennis players suffering from elbow pain believed that it was onset by playing tennis (Priest et al., 1980b). A statistical study by Priest et al. (1980a) on 2633 average tennis players revealed that 31% suffered from elbow pain at some time during their playing careers. These statistics were supported by Engel (1995) who claimed that 50% of regular tennis players will suffer pain in the elbow at least once in a lifetime. Amongst a population of 81 recreational tennis players, 81 percent associated the symptoms of tennis elbow with the backhand stroke (Nirschl, 1974).

The pain on the inside of the elbow results from the irritation of the common wrist flexor attachment on the medial epicondyle that is usually associated with the vigorous wrist flexion actions in serving or forehand drives (Roussopoulos & Cooke, 2000). Pain on the outside of the elbow is from irritation of the common wrist extensor attachment (lateral epicondyle) that is usually associated with errors in one-handed backhand technique (Bernhang et al., 1974; Blackwell & Cole, 1994; Giangarra et al., 1993; Roetert et al., 1995).

The Priest et al. (1980b) study investigated which strokes were associated with the onset of elbow pain. Table 1.3 shows the results, suggesting that it is possible to implicate more than one stroke. Further investigation by Priest and Braden examined the most painful tennis stroke and respondents cited the backhand (38%) as the most painful, followed by the serve (25%) and the forehand (24%). Men were observed to be twice as likely to regard the backhand stroke as the most painful stroke compared to the forehand; women were shown to be almost equally divided between backhand (32%) and forehand (27%).

Roussopoulos & Cooke (2000) suggest the physical stimuli possibly causing injury:

- A single sharp impulsive stress and strain to the muscles, as from a badly hit ball
- An accumulation of 'normal' or slightly high stresses, from prolonged playing
- A sharp vibration in the loaded muscle, as from a badly hit ball
- An accumulation of many vibrations, each one not in itself dangerous
- Any combination of the above

None of the published research has yet established whether any or all of these stimuli are responsible. Therefore many different treatment approaches exist. Segesser (1985) suggested that tennis racket oscillations in the range of 80-200 Hz are likely to contribute to the development of tennis elbow. In contrast Knudson (1991) argues that impulsive loading (initial shock) in tennis is the likely mechanism of TE since only these large forces can create the recoil of the racket that rapidly stretches the muscles of the forearm.
Table 1.3: Strokes associated with elbow pain, subjects were able to implicate more than one stroke

<table>
<thead>
<tr>
<th>Stroke</th>
<th>Women</th>
<th>Men</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backhand</td>
<td>58%</td>
<td>61%</td>
<td>60%</td>
</tr>
<tr>
<td>Forehand</td>
<td>52%</td>
<td>42%</td>
<td>46%</td>
</tr>
<tr>
<td>Serve</td>
<td>47%</td>
<td>43%</td>
<td>45%</td>
</tr>
<tr>
<td>Backhand volley</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Overhead smash</td>
<td>15%</td>
<td>14%</td>
<td>15%</td>
</tr>
<tr>
<td>Forehand volley</td>
<td>15%</td>
<td>12%</td>
<td>13%</td>
</tr>
</tbody>
</table>

1.4.1 Etiology

There are many contradictory opinions to the main cause of tennis elbow. The numerous citations for the pathology of the injury are varied and often speculative. Lateral epicondylitis was first described by Runge in 1873 as “tennis elbow” (Roetert et al., 1995). It is a debilitating condition in which the onset of symptoms may be sudden or gradual (Kamien, 1990; Priest et al., 1980b; Renstrom, 1994). It has been typically found that the average length of time taken for players to notice tennis elbow symptoms is 9.1 years from when they first begun playing (Priest et al., 1980a). The literature is generally consistent in that tennis elbow is degenerative in nature. Priest et al. (1980b) suggest that age, frequency of play, and flexibility deficiencies in the forearm extensor muscles may lead to an increase in the likelihood of developing tennis elbow. The lesion can occur at any age but is statistically more likely to manifest in the 35 – 50 age group, suggesting that age is a contributory factor (Kamien, 1990; Peters & Baker, 2001; Pluim, 2000; Renstrom, 1994). Priest et al. (1980b) also found that frequency of play had a direct relationship with pain. The more a player plays, the greater the tendency to develop tennis elbow. It has been suggested that a player’s ability could be an aggravating factor of tennis elbow. Given that the incidence in professional tennis players is much lower than that of the recreational player, this hypothesis could be valid (Blackwell & Cole, 1994; Peters & Baker, 2001). Reasons cited include a faulty technique, such as improper body movement and inefficient ball striking (Hennig et al., 1992; Matsuhisa et al., 2002; Roetert et al., 1995). Even though sufferers of tennis elbow have reported pain when forehands and serves are hit, the backhand has usually been found to be the most painful stroke (Pluim, 2000; Priest et al., 1980b; Roetert et al., 1995). According to Matsuhisa et al. (2002) this is because the extensor muscles which are connected to the lateral epicondyle are mainly used in the backhand stroke.

Figure 1.14 illustrates the location of the lateral epicondyle, the muscle believed to be the common problem in tennis elbow. Generally the pathology of the injury is believed to be caused by microscopic tears occurring in the tendon of the extensor carpi radialis brevis (ECRB) muscle, resulting in inflammation and pain (Renstrom, 1994). Tennis elbow affects the muscles of the forearm that control the
hand and wrist movements. Tennis elbow is agreed to be the inflammation of, and perhaps tearing in the tendon attaching the arm extensor muscles, especially the extensor carpi radialis brevis to the lateral epicondyle of the humerus (Cooke et al., 2002; Kamien, 1990). A player experiencing tennis elbow suffers a localised ache across the humeral lateral epicondyle which would be made worse by resisted extension of the wrist and pronation of the forearm (Field & Altchek, 1995). According to Engel (1995), the lesion can be described as “micro and macro tears in the conjoined tendon insertion of the wrist extensors at the humeral epicondyle”.

### 1.4.2 Causes of tennis elbow

As there is no universally agreed cause of tennis elbow, it is only possible to discuss the potential causes and theories supporting their roles. Table 1.4 lists a summary of some of the potential causes of tennis elbow discussed in the following sections.

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### Equipment

The use of unsuitable or incorrectly sized equipment has been hypothesised to initiate tennis elbow. Equipment factors such as balls, racket material, mass, balance and flexibility and even the court surface may aggravate the condition.

Renstrom (1994) and Pluim (2000) suggest that a player using dead, wet or pressure-less balls would be more likely to suffer from tennis elbow because the impact against the racket would be
increased. In turn they possess a lower coefficient of restitution and require more force to produce the same shot speed. They recommend that players suffering from tennis elbow should use new, pressurised tennis balls.

According to Carroll (1985), court factors such as unpredictable bounce, which influences a player's technique, and speed of the court (producing higher ball velocities therefore creating greater arm stress) can lead to tennis elbow symptoms. Slower court surfaces are recommended as they generate lower ball speeds giving a player more time to prepare for the shot Carroll (1985).

A loosely strung racket generates power, a tightly strung one assists control, and strings return 90-95% of energy they receive from the incoming ball. Pluim (2000) said that the dwell time of the ball on the racket strings can be increased by lowering the tension of the string. The longer the contact, the longer the duration of the shock of the ball, therefore reducing the magnitude of the force at any one time. However, Kawazoe et al. (2002) concluded that looser string tension was not an effective remedy for tennis elbow.

The grip has also been hypothesised to be a factor contributing to the occurrence of tennis elbow. Grip size, strength and material have all been considered. The circumference of most grips range from between 10.5cm-12.4cm, (sizes are labelled from 1-7). Pluim (2000) concludes that a grip size that is too large or too small may lead to problems. An incorrect grip size would force the player to grip the racket too tightly to prevent it from twisting, thus increasing the risk of tennis elbow (Brody, 1989). Bernhang et al. (1974) concluded that using the largest grip size that is comfortable is the most effective way of controlling this torque.

Renstrom (1994) suggest that there has been an increased incidence of tennis elbow since the early 1980’s when rackets made from diverse materials, such as composites were introduced. These composites do not absorb ball impact vibrations as effectively as wood. However, Kamien (1990) deduces that there is no evidence to suggest that the incidence of tennis elbow has changed and the rise in cases could be due to an increased popularity in the sport. Pluim (2000) suggests that using a composite racket with good damping qualities reduces the load on the arm.

Brody (1981) defines three sweet spots on the racket, areas where the rebound velocity of the ball is greatest and impact shock and vibration are minimal. If the player does not hit the ball in the sweet spot, a loss of ball control and velocity, and an increased load on the arm will result (Pluim, 2000). Elliott et al. (1980) demonstrated that oversized rackets had lower vibration levels and higher rebound velocities than their conventional counterparts. Increasing the size of the racket head can also increase its polar moment of inertia to prevent it from twisting from off-centre impacts (Pluim, 2000). Hennig et al. (1992); Tomosue et al. (1991) both reported that in the case of off centre hits, the amplitude magnitudes of the wrist joint and the racket handle showed approximately 2–3 times and approximately 1.5 times of those of the centre impact, respectively.
Rackets vary in weight between 275–360 grams. Renstrom (1994) observed that tennis elbow is more likely to occur in players who use a heavy racket which produces more momentum and places greater strain on the muscles in the forearm. Pluim (2000), conversely, proposes that a heavier racket is preferable as there will be less shock transmitted to the arm. He suggests that the greater the mass of the racket, the greater its ability to absorb shock. Other studies indicate that the weight of the racket does not influence the incidence of tennis elbow (Carroll, 1985).

A “stiff” racket is a racket that does not bend very much on impact. It is suggested that a more flexible racket is kinder to the arm as the flex will absorb some of the shock and spread it over a longer period (Hennig et al., 1992). However, stiffer rackets increase the muscle force that is required during the swing of impact while also increasing the stress on the elbow (Renstrom, 1994). The perceived effects of the racket are significant, such that 70% of players changed their rackets due to experiencing elbow pain (Priest et al., 1980b). Of those who changed their rackets, 69% were improved, 30.5% experienced no difference and 0.5% were made worse. There is significant investment amongst major racket manufacturers for racket vibration systems. Researchers have questioned the effectiveness of market available string-mounted vibration dampers. Tomosue et al. (1994) reported that the vibration damper significantly reduced the amplitude of vibrations at the handle and in the wrist. They concluded that the damper lessened string vibrations, which had an evident effect on frame vibrations. Brody (1989) found that both commercially available and homemade dampers eradicated string vibrations quickly and effectively. This was supported by Stroede et al. (1999) who concluded that this was possible as the mass of the damper is significant when compared with the mass of the strings. However, the mass of the damper is not significant when compared with the mass of the frame so dampers installed in the string bed cannot damp a significant amount of the frame vibrations. They also concluded that the vibration dampers do reduce string vibrations but have no effect on the lower frequency, higher amplitude racket vibrations that are transmitted from the racket face to the shaft and handle. Roetert et al. (1995) concurred and suggested that no anti-vibration device in the strings, regardless of the shape, size or material is going to stop frame vibrations.

Grip Strength

Hatze (1976, 1993) and Elliott et al. (1982) both report that a tight grip will result in the increase of ball rebound velocity therefore increasing the magnitude of the vibrations transmitted to the arm. However, contrary to these studies, other researchers have claimed that the ball rebound velocity is independent of the firmness of the grip (Baker & Putnam, 1979; Brody, 1995; Liu, 1983). Brody (1989) also found that the damping time depended on how tightly the racket was being gripped and where the grip force was applied.
There are two main reasons for investigating the forces transmitted to the hand during tennis strokes. The first is to examine the relationship between grip firmness and rebound velocity and the second is to establish a relationship between grip firmness and the transmission of impact forces to the hand. The impact force loads experienced in tennis have been hypothesised to contribute to tennis elbow. The physical stimuli that have been put forward as a possible cause for the injury are excessive stroke production loads pre-impact, excessive shock loads due to impact and excessive residual vibrations post impact. It is likely, however that a combination of the above is responsible for tennis elbow.

Vibrations from impact

The idea that high frequency vibrations generated by ball impact may be related to tennis elbow was first proposed by Hatze (1976). He reported that the ball was in contact with the strings for 4 ms but that the vibration of the racket continues for 40 ms afterwards; he speculates that these vibrations may initiate tennis elbow. This notion has been pursued by many researchers.

It seems unlikely, however, that vibration alone causes tennis elbow (Kamien, 1990). In this study it was reported that the mean number of years of playing tennis before acquiring tennis elbow was 22.6. Furthermore 88.5% of those who suffered from tennis elbow did not have a recurrence of the condition. Therefore, it is difficult to substantiate why it would take more than 20 years of vibrations to produce tennis elbow and then, after it had improved, rarely produced again. It is possible that vibration may not directly cause tennis elbow but it is simply an aggravating factor when a player has sustained it.

When the racket hits the ball, a large amount of the energy involved results in the deformation of the ball, strings and racket frame. Some of the energy is returned back into the ball in the form of kinetic energy, some is stored in the frame and the string deformation leads to vibration (Roetert et al., 1995). The racket will continue to vibrate until all this energy is dissipated. There are many ways of dispersing this vibration, including the grip, racket construction and vibration absorbers. However the most effective way of damping this vibration is through the human hand (Brody, 1989; Elliott et al., 1982; Hatze, 1976).

The position of impact is an important factor in both the resulting impulse and frame vibration. Roetert et al. (1995) and Casolo et al. (2000) explain that the point of impact on the racket where the resulting vibration of the frame is at a minimum is called the node of the fundamental mode of vibration, also known as the "sweet spot".

Many researchers have investigated the vibration of the limb during and after the impact from a tennis ball. Measurement sites typically include a knuckle of the playing hand and the bony protrusions
at the wrist and elbow. The bony nature of the sites permits good consistent measurement of the vibration from impact whereas pulpous areas can produce erratic results (Hennig et al., 1992).

Several investigators (Cundiff, 1976; Dong et al., 2004) suggested that vibration energy absorption may be a significant factor in regards to vibration injuries. There are a number of reports that have studied the transmission of vibration to the hand and arm (Reynolds et al., 1977a; Sorensson & Burstrom, 1997). However, it should be noted that for the most part, the research carried out into how the hand-arm system reacts to vibration has been concerned with continuous levels of vibration rather than short duration impulses resulting from ball impacts. Burstrom & Lundstrom (1994) reported that the energy absorption in the hand-arm system was measured in the frequency range 4–1000Hz. They stated that the sensation and transmission of vibration at the hand depends not only on the vibration intensity but also on the frequency, the contact area, the direction of the vibration stimulus, the force of grip, flexion of the elbow and skin temperature.

Reynolds et al. (1977a) observed that the hand and arm are complex continuous elastic systems in which both potential energy and kinetic energy can be stored. Potential energy is stored as a result of the relative compression or expansion of adjacent tissue. Kinetic energy results from the motion of the tissue in the hand. However, the hand was found to be highly damped, which implies that all of the energy initially transferred to the hand is not stored in the form of potential or kinetic energy, but absorbed by the tissue in the hand and arm. The investigators found that the intensity of vibration has a strong influence on the energy absorbed by the hand-arm system. They suggest the explanation for this could be that when the stimulus amplitude increases, a larger part of the hand-arm system is mechanically activated. Thus the dynamic mass and the volume of the part of the system where energy is absorbed increases, allowing the system to absorb more energy. These findings were confirmed by Burstrom & Lundstrom (1994) who also suggested that biological factors influence energy absorption. A larger biological size gives a higher energy dissipation, which could explain why women have a lower absorption than men.

Several studies have reported frequency dependence in the transmission of vibration (Reynolds et al., 1977a; Sorensson & Burstrom, 1997). The investigators observed that at low frequencies (<40Hz) individuals perceived the sensation of vibration up to the shoulder. As the vibration frequency was increased, vibrations at frequencies above 100Hz tend to be isolated to areas of the hand and fingers directly in contact with the vibrating surface. At frequencies below 100Hz, much of the vibration is directed into the hand and arm via the fingers. Less than 10% of vibration at frequencies above 250 Hz was transmitted to the wrist and beyond (Dong et al., 2004). Lundstrom (1984) investigated the effect of location of vibration. This was accomplished by subjecting eight regions of the hand to four frequencies. He found that the distal phalanx was more sensitive than the distal palm at low frequencies (<65Hz) but less sensitive at high frequencies (125Hz).
Burstrom & Lundstrom (1994) and Maeda & Okauchi (2002) reported that an increased hand grip force leads to an increase in absorbed energy and state that the reason for this could be that the energy absorption depends on the viscous elements of the hand-arm system. The viscous elements are influenced by muscle tension. The higher the tension, the more vibration is allowed to put a larger part of the hand-arm system in motion.

### Technique

It is believed that the incidence of tennis elbow in professional tennis players is lower than that of a recreational tennis player (Blackwell & Cole, 1994; Peters & Baker, 2001). Investigating the ability levels of players in their study on elbow pain, Priest et al. (1980a) found that only 6% of beginners and 20% of advanced beginners had ever experienced elbow pain. Of intermediate, pre-tournament and tournament groups of players, an average of 34% of players had experienced elbow pain. Of all the players surveyed, 76% of players who experienced elbow pain were in the top three ability levels. These findings may be explained by considering that better players may play more frequently, for longer duration and therefore have more chance to develop symptoms. However, to some extent this evidence does contradict the assumption that beginners, weekend players and players with lower ability are more likely to develop tennis elbow (Priest et al., 1980b). The scarcity of professional tennis players reporting tennis elbow symptoms may also be explained by the Priest et al. (1980b) statistic that the average age of the respondents with current elbow pain was 43 years, whereas those without pain was 36 years. It may be that professional players retire from the game of tennis before they reach a stage of physical degeneration that allows the appearance of tennis elbow symptoms. Blackwell & Cole (1994) supported that age may be a factor by showing that force and flexibility deficiencies in the forearm muscles and a lack of movement accuracy lead to an increased load on the lateral epicondyle. Work by Giangarra et al. (1993) suggests that the decreased incidence of tennis elbow with the two handed backhand was due to faulty swing mechanics of the single-handed backhand rather than any help provided the injured arm by the added arm. As previously mentioned, advanced players have been shown to use shorter durations of maximum grip pressure (Bernhag et al., 1974; Engel, 1995) and these top players have also been noted to produce a racket acceleration of nearly zero at impact (Brody, 1989; Hatze, 1976). These grip findings may help to explain the differences in technique between advanced and beginner players.

### 1.4.3 Treatment

There are many treatments for lateral epicondylitis. Some of these are developed specifically for tennis players who have developed the condition. Others are for individuals who have developed conditions from numerous means.
Equipment

Many players suffering from tennis elbow will attempt to change or alter their equipment in order to improve their condition. Priest et al. (1980b) discovered when probing treatments used by players for tennis elbow that 100% of players that altered their stroke as a remedial measure found it helpful. Individuals may also change to rackets such as those mentioned in Kotze et al. (2003). When testing these rackets on a sample of tennis elbow sufferers, 33% of the sample experienced no pain, 50% experienced definite improvement and 17% a slight improvement with none experiencing no improvement. The results for chronic sufferers were not as remarkable. None experienced no pain, 10% a definite improvement, 29% a light improvement and 61% no improvement. Players also use vibration dampers on their rackets to try and prevent improve discomfort from playing tennis, however, there exists no scientific evidence to suggest that string dampers have any influence on the vibrations from impact (Li et al., 2003; Stroede et al., 1999) Another popular solution is the wearing of an arm brace on the afflicted arm, the most popular method of treatment (Priest et al., 1980b). The mechanism of the brace works, by creating a new ECRB origin, producing a decrease in stress on the affected tension and allowing time for it to heal without interfering with activity (Boyer & Hastings, 1999). There are several types of braces. One compresses locally at the insertion of the wrist extensor tendons; another type applies compression over a larger area with a silicone pad; a third type of brace places a high-viscosity fluid pad at the forearm over the extensor muscles. The effectiveness of these three types of braces was investigated by Walther et al. (2002). The clasp braces showed an 8% reduction of integrated acceleration and no difference in the Fourier spectral analysis. The silicon pad braces demonstrated reduced integrated acceleration by 22% and a slight reduction in the dominant frequency of the Fourier analysis. The braces with the pad placed along the extensor muscles had the highest reduction of integrated acceleration (42%) and the peak of the resonance frequency was reduced in the Fourier spectral analysis. However, some of the braces that appeared to have excellent damping properties produced similar high first acceleration amplitudes compared with those with poor damping properties. The braces also did not influence the acceleration of the wrist or racket. The authors believed that the accelerations at the wrist are determined exclusively by the mechanical parameters of the racket, the playing skills and grip strength. The authors did report that although the braces with pads placed along the forearm extensor muscles had the highest reduction of acceleration, with 30-40% reduction in oscillation time, there was a high variability amongst players. In the sample examined by Priest et al. (1980b), 89% had found a tennis elbow brace/support to help their symptoms.

Medical treatments

There are many different courses of medical treatment for lateral epicondylitis. A brief summary of the main treatments is included in this section. Corticosteroid injections are a commonly used treatment
(Priest et al., 1980b). The injection is inserted into the painful area of the arm. Despite widespread use, scientific proof of the long-term effects have repeatedly shown that it has no significantly different effect from control groups (Boyer & Hastings, 1999). Ultrasonography is another popular treatment method and has been shown to improve patients after a period of 3–12 months, although Boyer & Hastings (1999) debate the accuracy of the studies. Similar, treatments to ultrasonography include cross-frictional massage, shock wave therapy and low-energy laser treatment. The most severe treatment would be surgery. Boyer & Hastings (1999) identify several surgical procedures, stating that each of the approaches have been developed by different surgeons, all reporting success with their technique. In general surgery, attempts are made to inspect the attachment site of the ECRB muscle and assess the damage is occurring from the lateral epicondyle. Depending on the surgeon, different remedial measures will be taken.

Alternative treatments

An alternative course or treatment that some individuals may choose is the application of acupuncture to the injured region. Studies reviewed by Boyer & Hastings (1999) have shown some positive results on patients receiving acupuncture treatment. Although, there may appear to be a good short-term effect of classical acupuncture, but there appears to be no lasting effect that exceeds untreated tennis elbow over the long-term. Other approaches include the prescription of remedial exercises or the application of heat or cold to the site of injury before and after tennis participation. The final most popular treatment for tennis elbow is a rest period. Priest et al. (1980b) had found that 83% of player surveyed believed that the rest had helped their condition.

1.5 Summary of literature

There is a breadth of research regarding all aspects of tennis. This chapter has attempted to examine and discuss those studies of most relevance to the investigation and development of a customisable handles system. During the thesis more related studies will be discussed as relevant. The identification of numerous aspects of the racket handle to be customised determined a requirement for a method to refine the possible research areas to direct the project. In general, a lack of coherent data has been produced from the various research studies examined. This lack of agreement among the key researchers makes it difficult to select a specific area of the racket handle to investigate. The lack of agreement also makes assumptions for test protocols based on existing literature difficult and therefore it may be necessary to further research any specific data to be measured.
Chapter 2

Rapid Manufacturing

2.1 Introduction

Rapid manufacturing (RM) is a fairly new concept that has evolved from the development of rapid prototyping (RP) technologies. The term rapid manufacturing is generally used to describe the use of additive manufacturing processes at some stage in the production chain. However, Hopkinson et al. (2006) defined rapid manufacturing as 'the use of a computer aided design (CAD)-based automated additive manufacturing process to construct parts that are used directly as finished products or components'. The term 'additive' manufacturing is also used and although currently the RM processes work by 'layer' manufacturing, future developments may not be conducted in the same fashion so a more general description is most suitable. The 'layer' based systems were initially developed for rapid prototyping. Although there are examples of RM being undertaken, these are typically performed with existing RP systems. Currently, few RP methods are used as traditional manufacturing processes due to issues with surface finish, resolution, and accuracy that need to be overcome. However, more modern machines are now being designed for the production of end-use parts as required by RM, and it is estimated that true RM systems will become available within 5-10 years (Hague et al., 2004).

The use of RM provides an opportunity for advanced design options and also raises issues influencing the design, distribution and involvement of the consumer in producing a variety of products. This chapter will discuss the key processes and the predominant issues for the implementation of rapid manufacturing for the production of customised sports grips.

2.2 Rapid manufacturing processes

Many of the current processes used for rapid manufacturing were initially developed for rapid prototyping (RP) and cannot be considered as full RM machines since the produced parts have inherent drawbacks and limitations (Hague et al., 2004). Many of the drawbacks relate to surface finish, dimensional accuracy and range of materials available to each of the processes when compared to conventional processes such as injection moulding. The process of producing a RM part is relatively
simple. First, a 3D CAD model of the part is produced. The CAD model is formatted into an .stl file, where the surfaces of the part are decomposed into a series of tessellating triangles. The .stl file can then be sliced horizontally by the software of the manufacturing process. Each individual slice of the .stl file is essentially a 2D profile of the shape of the part. These 2D shapes are then reproduced by the manufacturing process, with each slice deposited consecutively on top of each other, forming the 3D model. An example of the the 3D CAD model process is shown in Figure 2.1. Swift rapid manufacturing developments have caused the production capabilities of the processes to outstrip the capabilities of CAD, where the most time-consuming aspect of producing a RM part has become the time spent producing the concept in CAD.

![CAD model](image1.png) ![.stl file](image2.png) ![layer data](image3.png)

**Figure 2.1: Conversion of CAD model to .stl file to layers produced by .stl file**

As rapid technologies are still emerging, some of the current processes will become obsolete. New processes will emerge and become key enablers to the concept of rapid manufacture. According to Upcraft & Fletcher (2003), there are five main manufacturing processes that categorise the approaches used by the manufacturing systems in RM and RP.

- Curing process; A photo-sensitive polymer is exposed to a light source in order to harden/cure the polymer.
- Sheet process; Thin sheets of a material are cut to shape and stacked on top of each other.
- Dispensing process; A material is melted and then deposited either as a hot filament or as individual hot droplets.
- Sintering process; A powdered material is sintered/fused together using a laser source, typically a laser beam.
- Binding process; A liquid binder is deposited onto a powdered material to bind the powder together.
According to Upcraft & Fletcher (2003) a survey in 1999 identified 40 different RP manufacturing approaches. Some of these may be now well established and others may just be beginning to emerge as technology. Several of the approaches named may have become defunct since 1999 as processes are still being refined and the viable options are strengthening their market position.

A summary of the most popular RP/RM processes is given below, each of these processes are available to the Rapid Manufacturing Research Group at Loughborough University. It should be noted that laser sintering was the main focus process for this project.

**Stereolithography**

Stereolithography (SLA) is one of the oldest RP technologies, dating back to the mid 1980s. SLA is often favoured for the production of parts because they can achieve a complex geometry and surface finish comparable to conventionally machined components.

**Method**

A vat of photocurable polymer contains a platform upon which the part is built and the platform rises and falls within the vat. The platform moves to just below the surface of the liquid polymer (0.05-0.25 mm) and a UV laser is used to trace the cross-section slice of the part. Solidification occurs where the laser hits the polymer. The platform then moves down the distance of one slice (0.050-0.250 mm) of the part, and the laser draws the next slice on a fresh layer of liquid polymer. This slice of the part solidifies on top of the previous set slice. When all the slices have been traced by the laser, the platform is removed from the vat and excess liquid polymer is drained off the completed part. The part is then finally cured in an ultraviolet oven to ensure complete cure of the polymer.

![Figure 2.2: Stereolithography process (source: http://www.techok.comsla.html)](http://www.techok.com/sla.html)
Laser sintering

Laser sintering is the principal manufacturing process used in this project due to the availability and suitability of the materials. The process was first developed by the University of Texas in Austin and was commercialised by the DTM corporation in 1987. There exists two major manufacturers of LS systems: 3D systems, who have proprietary use of the term selective laser sintering (SLS) to describe their process, and EOS, a German company who produce multi-purpose sintering equipment. Laser sintering can be used to process almost any material, provided it is available as powder and that the powder particles tend to fuse or sinter when heat is applied (Kruth et al., 2003). Powders that posses low fusion or sintering properties can be laser sintered by adding a sacrificial binder material (typically a polymer binder) to the powder. After sintering these types of powder, the sacrificial binder can be removed by debinding the ‘green’ part in a furnace. The part properties (surface quality, part density, etc.) of laser sintered parts can be influenced by varying the process parameters such as laser wavelength (type of laser), laser power, scan speed and spacing and powder characteristics such as particle size, powder composition, etc.

Method

The typical layout of an SLS system is shown in Figure 2.3. The process works by depositing a layer of powdered material, from one of the feed pistons using a roller, on the build platform. A laser beam traces out the cross-section of one slice of the part in a raster sweep motion. Where the laser beam hits the powder the affected particles fuse/sinter together. CO₂ lasers with wavelength of 10.6 μm are generally well suited for sintering polymer powders (Kruth et al., 2003). Another layer of powder is then deposited on top of the previous layer again using the roller mechanism, and another slice of the part is sintered on top of the sintered material in the previous slice. The unsintered powder in each layer can act as a support structure for the part itself. This is advantageous as complex structures
and closed geometries can be built, as long as provision for unsintered powder removal is included. A significant advantage is that other processes require not only the construction of ancillary support structures, but sufficient post-processing to remove formed support structures, which can influence design and cause surface finish issues. When completed, parts are encased in the unsintered powder, known as a powder cake. The parts need to be broken free from the excess powder and the unsintered powder cleaned away from the part, using processes such as fine-grit blasting or even compressed air blasting. Once completed further non-essential post-processing such as sanding, polishing, coating or infiltration can be performed as required.

Fused deposition modelling

Fused deposition modelling (FDM) was initially a concept modelling classification of the RP process, due to the fact that the models produced were generally non-functional in terms of strength and surface finish when compared with other processes. However, this process has developed and the parts are improving.

Method

A filament of material is extruded from a fine nozzle and deposited onto a platform (Figure 2.4). The nozzle moves in the X-Y plane so that the filament is laid down to form a thin cross-sectional slice of the part. The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. As the extruded filament is hot, it bonds to the material in the previous slice. A second nozzle is used to extrude a different material in order to build-up support structures for the part where needed. Once the part is completed the support structures must be broken away from the part.

![Diagram of Fused Deposition Modelling process](source: www.xpress3d.com/FDM.aspx)
Multi-jet modelling

Multi-jet modelling (MJM) is another process which was primarily used for concept modelling. MJM is sometimes described as inkjet printing in three dimensions. It has mainly been developed to allow design teams to quickly evaluate concept form, and function, with little regard to the actual material properties of the part.

Method

A print head containing many tiny jets in a linear array passes in the X-Y plane over a platform (Figure 2.5). Where material needs to be deposited, a jet dispenses a droplet of thermo-plastic polymer. Any number of the jets in the array can be activated simultaneously, ensuring a rapid dispense rate of material when required. The hot droplets of the material bond to the previous slice of the part that has been printed. Thin support pillars are also built where needed, to maintain required part geometries, using the same thermo-plastic polymer. When the current slice of the part (including any ancillary support pillars) is completed the platform is lowered relative to the print head and the next slice is printed. When all the slices have been completed, the part is removed from the machine and the supports structures broken away.

Three-dimensional printing

Three-dimensional printing (3DP) is another of the proof of concept processes. However, the processes are developing and appropriate impregnation of finished parts can produce more durable parts.

Method

A feed chamber contains a quantity of specially prepared corn starch. When required the piston is raised to deposit powder in front of a feed roller (Figure 2.6). An adjacent build chamber operates in a similar manner with a piston determining the height of the build chamber. A feed roller traverses the build material horizontally, spreading new material from the feed chamber evenly over the build.
chamber. Mounted onto the feed roller carriage is a binder cartridge, which deposits a binder solution as appropriate for the current slice of CAD data as it travels. The printing process repeated as the build piston is lowered and new material is deposited over the build chamber surface using the feed roller. When all layers have been printed, the untreated corn starch is cleaned from the part and the part removed from the build chamber.

Figure 2.6: Three-dimensional Printing process
2.3 The use of rapid manufacturing

2.3.1 Why rapid manufacturing?

One of the principal advantages gained from rapid manufacturing versus conventional manufacturing methods is that different design methodologies may be employed. Rapid manufacturing eliminates the need for tooling in the production of parts and facilitates the production of parts where difficult or impossible machining would be required. These developments have presented a wide range of possibilities for low to medium volume part production using rapid manufacturing, where it may be economically viable to produce parts in single part batches. This can help to further increase the involvement of the consumer in the product design and potentially allow the product manufacture to be brought to the point of sale, increasing customer satisfaction. The removal of tooling from the production process can render many of the restrictions of 'Design for Manufacture and Assembly' (DFMA) obsolete. In conventional manufacturing, there is generally a direct link between the complexity of the part produced and its cost. In rapid manufacturing, the complexity becomes independent of cost since RM techniques are able to produce virtually any geometry. Due to the flexibility and the lack of tooling required to manufacture parts, rapid manufacturing is considered to be the most suitable process to develop a customised grip system for the mass market.

2.3.2 Design for manufacture and assembly versus design for rapid manufacture

Design for Manufacture

Generally, a designer works within the context of an existing production method that can only be minimally modified. In some cases, the production system may be modified or redesigned in conjunction with the design of a product. This is the concept of 'design for manufacture' (DFM) and is one in which considerations for the manufacture of the product are made at the earliest stages of the design such that parts can be produced easily and economically. Some principals of the DFM process are used to enable efficient manufacturing, i.e. developing modular design, using standard components and designing for multi-use. However, the main thrust of the principal is to design for ease of manufacture. The guidelines vary with the manufacturing processes to be used but according to Boothroyd et al. (1994), DFM is useful because it not only reduces the product costs, but also shortens the time to market. They suggest that up to 70% of a product’s costs are influenced by the design phase, while as little as 5% of the products cost is spent on the design phase. There are many different guidelines for DFM, each depending on the production processes used. With the majority of the initial RM processes taking the form of 'plastic' processing systems, the most obvious competition will be with injection moulding (Hopkinson & Dickens, 2003).

Design for Assembly
Design for assembly (DFA) is a similar concept to DFM except it relates to products that are produced from the assembly of several component parts. By adopting the guidelines at the design stage it is possible to produce reductions in manufacturing cost and ease of assembly. A brief summary of the guidelines from various sources (Boothroyd et al., 1994; Kalpakjian & Schmid, 2001):

- **Reduce parts count.** By eliminating unnecessary parts, combining parts, and eliminating or reducing the number of fasteners it is possible to reduce the assembly complexity and therefore reduce production times and overall product cost.

- **Reduce handling time.** Designing parts so they can be more efficiently handled and manipulated during assembly can result in improved assembly process.

- **Ease of insertion.** This concept involves designing parts that are easy to align, easy to insert and self-locating with no need to be held in place before insertion of the next part. Also intuitive design of parts can minimise part placement errors, reducing the number of defective products.

### Design with rapid manufacture

Designers have generally been restricted in what they can produce, as they have had to design for manufacture and assembly, ensuring that their designs can be manufactured in a certain way, using a certain process. As RM is a tool-less process, the guidelines imposed on design by DFM and DFA become unnecessarily restrictive. Factors such as wall-thickness, weld lines, sink marks, ejection pins, gate marks and draft angles are of no concern for parts produced by RM. The absence of tooling allows geometric freedom with changes to part geometry being restricted predominantly by the process build volume and only requiring modification of the CAD model. This allows properties such as variable wall thickness to be easily incorporated into designs, without the design incurring large tooling and manufacturing time costs. The additive nature of the current RM processes means that issues with material flow and cooling are not a factor. It is possible to produce complex models with injection moulding, however these are often at great expense in tooling and with considerable tool setup time and long lead times, with each modification of a design requiring new tooling. Conventional part production theory dictates that as the complexity of a part increases, so does the cost of production. With RM processes, the cost is generally dictated by the volume of the build, therefore parts can be given increased complexity without significantly altering production costs (Hague et al., 2003a,b).

The ability to produce complex parts has potential benefits when analysing DFA guidelines. RM processes can make it possible to consolidate components that would usually form an assembly into a single part. LS is particularly suitable for this strategy as the ancillary powder forms a support around the sintered powder of the part. The consolidation of parts is not always desirable if certain components in an assembly require periodic replacement. However, in other applications, the removal
or reduction of the need to assemble the components can improve production cost and time and also potentially facilitate the optimisation of part performance. Figure 2.7 shows an example of part consolidation of a multiple component aircraft ducting into a single part using the SLS manufacturing process.

![Figure 2.7: Example of consolidation of multipart aircraft ducting (left) into one part (right) using LS process (source: www.3dsystems.com, 2004)](image)

Hague et al. (2003a) suggests that design for rapid manufacture will eventually develop to "design for stereolithography" or "design for laser sintering", where common rules will apply but considerations due to material properties and process idiosyncrasies will need to be observed. It is also noted that there will still be a need to consider design for assembly with regards to the inclusion of non-RM components and design for maintenance in order to keep products in working order.

### 2.4 RM materials

The use of rapid manufacturing for the manufacture of parts poses a few issues that need to be addressed. It is difficult to apply conventional material selection processes for parts to be produced using RM processes due to the small range of available materials and the non-homogenous material properties. Therefore material selection is generally decided by what materials there are available and which of those provide the most suitable properties for the core functions of the part. In general the range of materials is small compared to the range of materials available for conventional manufacturing processes such as injection moulding. RM materials have become based on either popular conventional materials i.e. Nylon 12 and Duraform PA or designed to replicate certain properties of conventional materials without possessing the full range of properties i.e. Accura 60 and the transparent properties of polycarbonate. The cost of the materials available for RM processes are much higher than equivalent volumes of conventional materials, typically due to their specialised nature and comparatively small uptake.
There have been concerns regarding the lack of isotropy of the materials produced using RM processes. As the materials are fabricated in a layered fashion it is possible that the materials may behave in an anisotropic manner. To investigate, Hague et al. (2004) produced ISO standard tensile test bars in three different orientations (Figure 2.8). These bars were produced using the SL7560 resin for SLA and the Duraform PA powder for LS. For SLA, the build orientation produced little anisotropic effect on the parts produced, with a maximum variation of properties of less than 5% for the three orientations. In comparison the LS parts showed a significant degree of anisotropy, as shown in Table 2.1, with variations in material properties exceeding 5%. Hague et al. (2004) proposed that the anisotropy found in laser sintered parts is provoked by the scanning methodology employed by the laser sintering machine used, and the nature of the scanning it employs for producing the solid sections of each layer, as the laser only hatch-scans in the 'x' direction for the solid sections of each layer.

Table 2.1: Isotropy and anisotropy test results ±1 s.d. for Duraform PA (Hague et al., 2004)

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Build orientation</th>
<th>Flat</th>
<th>Edge</th>
<th>Upright</th>
<th>Max % variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{UTS}$ (MPa)</td>
<td>48.70 ±1.20</td>
<td>44.70 ±3.73</td>
<td>40.90 ±0.89</td>
<td>19.0</td>
<td></td>
</tr>
<tr>
<td>$E_t$ (MPa)</td>
<td>2047.00 ±21.58</td>
<td>1944.00 ±82.9</td>
<td>1817.00 ±8.94</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>$\sigma_f$ (MPa)</td>
<td>60.30 ±1.61</td>
<td>63.7 ±1.88</td>
<td>57.7 ±1.05</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>$E_t$ (MPa)</td>
<td>1104.00 ±32.2</td>
<td>1150.00 ±35.9</td>
<td>1045.00 ±21.59</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>$a_i$ (kJ/m$^2$)</td>
<td>3.80 ±0.36</td>
<td>4.00 ±0.16</td>
<td>3.35 ±0.22</td>
<td>10.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.8: Build orientation of tensile test samples for isotropy tests (Hague et al., 2003b)

In addition to the isotropy tests Hague et al. (2003b, 2004) investigated the effect of build parameters on part performance, using impact tests for parts built in flat orientation. In a conventional impact test, a sample is produced and a notch is placed into the surface of the part using a notching machine. Using RM processes a notch can be incorporated directly into the built part. Two SLA resins and one LS powder were investigated in this testing, with the results in Table 2.2. The impact
resistance of the parts with the notch incorporated in the build exhibited greater impact resistance than those parts that were built and the notch added using the notching machine. It is proposed that this could be caused by the scanning motion of the laser used to build each layer, as the layer boundaries are scanned first and then the remainder of the slice area scanned.

Table 2.2: Impact strength of RP versus manufactured notch (source: Hague et al. (2004))

<table>
<thead>
<tr>
<th>Material (RP process)</th>
<th>Mechanically manufactured</th>
<th>Build process manufactured</th>
<th>Percent improved</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL7560 (SLA)</td>
<td>2.4</td>
<td>5.7</td>
<td>137.5</td>
</tr>
<tr>
<td>Acura SI40</td>
<td>2.5</td>
<td>4.2</td>
<td>68.0</td>
</tr>
<tr>
<td>Duraform PA</td>
<td>3.8</td>
<td>4.5</td>
<td>18.5</td>
</tr>
</tbody>
</table>

The effects of temperature on the material properties were also investigated by Hague et al. (2004). Since for many applications, the useful working envelope for material properties is important to ensure appropriate material selection. The Duraform PA material was shown to have a lower ultimate tensile strength (UTS) at ambient and lower temperatures than the two SLA resins. However, Duraform PA was shown to exhibit stable UTS characteristics over a wider temperature range (-40 to +50°C), with almost linear deterioration of the UTS properties as the temperature increased.

Most current manufacturing methods produce parts of homogenous material. Techniques such as over-moulding are used to combine two or more homogenous materials in one part. However, this creates a clear boundary between the materials. In the future, the use of additive manufacturing processes may enable the mixing and grading of materials in any desired combination, allowing materials with certain properties to be deposited where they would be most useful. This has implications on the functionality and aesthetics that can be designed into parts. One method proposed to achieve this is the sintering of dissimilar powders to produce new and revolutionary materials that would not be available to other processes.

It is believed that RM will become more prevalent when the properties of the materials that are produced become more acceptable and consistent. Materials research is one of the main stumbling blocks to the adoption of these additive manufacturing techniques for end-use parts and is currently under research.

2.5 Customisation

According to Campbell (2006) customisation is the process of taking a general product design concept and tailoring it to the needs of a specific customer. A product's value is increased by adding customisation, as it is acknowledged that customers will pay a premium price for a product that they feel is uniquely theirs. There exists different levels of customisation, each of which require different methods
to be achieved. The most intensive of these is the production of a wholly bespoke product: one that has been designed from conception for an individual customer and aims to satisfy the requirements of that customer and no others. This situation occurs rarely, but one example is a uniquely commissioned piece of jewelry. At the other end of the spectrum is the modification of one feature of an otherwise standard product. This can be achieved by either changing the product's colour or size. These could be configured with thousands of options to satisfy one person's tastes or a range of options to satisfy a group of customers. Between these two extremes lies the concept of modularisation. In this process, a highly customised product can be produced by presenting the customer with several options for a range of features of the product. This generates thousands of potential product configurations to satisfy the customer. This process has been used for many years by the automotive industry to satisfy consumer needs. The relationship between the type of customisation and the range of available options is depicted in Figure 2.9.

![Figure 2.9: Different types of customisation (Campbell, 2006)](image)

RM can be used to satisfy almost all methods of customisation. However it is thought to be most appropriate for creating an infinite number of choices for one or more features. A product can be customised in terms of aesthetics, fit and function. RM would allow every product to be made unique in some way. This becomes possible because RM is economically viable for part production of a batch size of one, whereas using conventional manufacturing methods it would be impossible to do so. This does not mean that each feature will be made separately, as some features may continue to be manufactured conventionally, but features that the customer demands could be changed as a response. However, certain product aspects may never become customisable due to concerns such as safety implications and the impracticality of having to fully inspect every iteration of a design.
Intellectual property issues can also limit the customisation of certain features as they could cause infringements on other companies' trademarks or patented designs.

2.5.1 Determination of features to customise

It is possible to customise almost every feature of a product if desired. However, a significant reason to use customisation is to add value to the product. Therefore, there is very little worth in customising a feature that does not add to product value. Campbell (2006) proposes that a functional analysis of the product design should be undertaken, which attempts to determine the relative contribution of each feature in a product towards its overall value. In the example used by Campbell (2006), the value of a toothbrush can be derived from the functionality of the handle, stem and bristles and its aesthetic appearance. By showing potential customers two alternative versions of the design and asking the customer how much they would be willing to pay for each, the value contribution of the aesthetic appearance can be approximated. This process becomes more complicated for products with many features. The outcome of the functional analysis is a list of possible product features with their relative values. These values should add up to the price that the product can be sold for. When applying a function analysis to a product that is to be individually customised, it must be performed differently, as it is possible that the product can be customised precisely to the individual's requirements. An estimation must be made as to how much extra a customer would be willing to pay for this personally customised feature. The final outcome of this function analysis would yield a list of features together with the extra price that the customer would pay for them to be customised. The designer would estimate how much it would cost to customise each feature using RM and incorporating the extra design required, increased manufacturing cost. The value index Equation 2.1 is then calculated.

\[
\text{Value index} = \frac{\text{extra price paid by customer}}{\text{cost of customisation}}
\] (2.1)

Features that yield the highest value indices should be selected for customisation as these will provide the greatest return on investment. As discussed previously, some features may not be suitable for customisation. Most notably, these features are critical to the safe operation of the product. Other features that may not be suitable are those that form part of the brand identity of the product.

2.5.2 RM role in customisation

The desire to customise products for an individual's use or body shape is not novel. However, this process is typically very labour intensive, requiring highly skilled workers, and is therefore very expensive. Customised products have been generally reserved for rich or elite consumers, with the general public typically purchasing mass-produced items. True customisation, where the whole product is designed with a single individual consumer in mind is still a far from feasible concept for the mass market. The
concept of 'mass customisation' is being employed to fulfil the current need for personalised products. Mass customisation is generally achieved by using the process of 'modularisation'. This is the production of modules that can be combined in varying configurations to allow some choice in the product, whilst still maintaining the economical benefits of mass production. An example of this procedure is observed in the sales of new cars, where customers can specify many of the car’s features to suit their needs. Each of the different features will have been produced using mass manufacturing principles, but by providing several different options for a variety of features it is possible to create thousands of possible combinations of car for the customer to select. It can be argued whether this freedom of choice is beneficial to the consumer, as it may generate a source of confusion.

RM may prove to be the beginning of economically viable customisation of products for the mass-market. Parts produced using RM could be modified to an individual’s requirements without a need to modify the production and processing methods used. This will help to enhance the occurrence of personalised customisation on commercially available products. Developments in consumer’s computer literacy, coupled with the spread of home internet connectivity enables the possibility that RM technologies will soon allow consumers to modify the design of the product they require. Products such as mobile phone casings, sunglasses, prosthetic parts and kitchen utensils are all items that may be modified in this way. For sports products, Nike is one company offering this type of service through their Nike iD site (www.nikeid.com), allowing customers the ability to customise shoes or apparel using a series of different colour schemes and to add their own name or symbol onto the shoe design. Only selected logos or names can be specified due to potential intellectual property infringements.

2.5.3 Importance of customer input

One of the concerns regarding customer input to the product concept is the need to maintain confidentiality in the design process. Ultimately, when capturing customer input these requirements should be developed into a product design specification (PDS). The requirements of a PDS can be either quantitative such as product weight or balance point of subjective, e.g. ‘I want this product to feel expensive’. Some qualities may be specific to a large group of the users, e.g. ‘the product must be safe to use’, others may be specific to the individual, e.g. ‘it must fit in my hand’. To capture this broad spectrum of requirements requires several techniques. It is generally found that the harder to capture qualities will often have the most impact on the product success. The product design requirements may be classified as follows (Campbell, 2006):

- Functional requirements
- Environmental requirements
- Ergonomic requirements
2.5.4 Capturing customer requirements

One method of capturing customer information is reverse engineering. Using probes or sensing devices, such as touch probes or laser scanners, the three-dimensional shape of an object or body part can be captured. These measures can then be used and manipulated to create custom products. One of the key issues when capturing this data is movements of the limbs whilst they are being scanned or the deformation of the limb scanned when it comes in contact with the product. In some niche markets this process of data capture is already occurring. Siemens and Phonak are using SLS and SLA to manufacture bespoke hearing aids from 3D scans of the consumer’s ear, ensuring optimal fit and comfort is achieved. It is also possible to gain information regarding customer requirements using methods such as questionnaires or online surveys. Consumers could use these methods to specify discrete levels of customisation such as handle size, product stiffness, product weight. It may be also possible to provide a continuum of suitable options for a consumer to select from. The most suitable values could either be specified directly by the consumer or determined from consumer’s responses to appropriate questions regarding product usage or preferences.

2.5.5 Customisation issues

A number of issues have been identified that need to be resolved to ensure the viability of customisation using RM. The ownership of intellectual property, product liability and product resale are all influenced if the customer is to have significant input on the design of the product. It is fortunate in sport that the general trend is for equipment to be proprietary to an individual and therefore few concerns over shared usage exist.

2.6 Cost of Rapid Manufacturing

One of the biggest influences on the uptake of a manufacturing process is the cost. In general the manufacturer knows the the cost the customer wants to pay, thus a reduction of manufacturing costs yields a better profit. This section examines costs associated with rapid manufacturing.
2.6.1 Material costs

The prices per kilogram of materials for rapid manufacture are considerably higher than those for conventional manufacturing processes. Table 2.3 shows a comparison of some material costs for three RM processes with those of conventional manufacturing processes.

<table>
<thead>
<tr>
<th>Process/material</th>
<th>Cost per kg ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereolithography/epoxy-based resin</td>
<td>175</td>
</tr>
<tr>
<td>Selective laser sintering/nylon powder</td>
<td>75</td>
</tr>
<tr>
<td>Fused deposition modelling/ABS filament</td>
<td>250</td>
</tr>
<tr>
<td>Injection moulding/ABS</td>
<td>1.80</td>
</tr>
<tr>
<td>Machining/1112 screw-machine steel</td>
<td>0.66</td>
</tr>
</tbody>
</table>

These figures would suggest that RM is unable to compete with conventional manufacturing processes, particularly when high production volumes are required. However, as the adoption of RM increases larger volumes of material will be used and economies of scale will result in the material cost decreasing. It is believed that RM can create products with zero waste, which is not strictly true as many of the processes require support structures to be included during the part's build. In the case of SLS, where support structures are negated due to the supporting nature of the powder; there are still restrictions on the re-use of powder. Manufacturer guidelines suggest that recycle should never exceed 67% of the total powder used in a build, due to the changes in mechanical properties caused by the thermal treatment occurring during manufacture. Furthermore, when producing parts requiring optimum product quality and consistency, an entire bed of new powder is required. This may be improved with further investigation into material characteristics as recycling becomes more effectively incorporated into RM systems.

In general, the labour costs associated with RM are lower than those for the machine and material costs. This varies with the part size, complexity and manufacturing process used. Other influences such as potential finishing costs, production volumes, and the hourly costs can increase these labour costs further. A general overview of RM performed with current RP machines gives an estimated cost breakdown of (Hopkinson & Dickens, 2003):

- Machine, 50-75%
- Materials, 20-40%
- Labour, 5-30%
2.6.2 Comparison of injection moulding costs with RM

The most suitable process for comparison to RM is injection moulding, as both are predominantly used for plastics. RM is more cost effective for smaller production runs, but high volume part production is better suited to injection moulding as the tooling cost is offset by the large part numbers (Keane, 1997).

Two studies of production costs of RM processes have been conducted (Hopkinson & Dickens, 2003; Ruffo et al., 2006a). Hopkinson & Dickens (2003) compared three rapid manufacturing processes and injection moulding. The RM methods analysed were stereolithography (SLA7000), selective laser sintering (EOSSP360) and fused deposition modelling (FDM2000). They considered ancillary factors, such as energy costs and building space, representing approximately 1% of the total production costs. Considerations for material properties, surface finish and accuracy of parts produced by RP were not made as the parts produced were designed for injection moulding. The costs for producing parts by RP processes were calculated assuming that each machine produces one part consistently for 1 year.

Three components of the cost breakdown for parts by RP processes were identified:

(a) machine costs
(b) labour costs
(c) material costs

Hopkinson & Dickens (2003) selected a small size part with complex geometry (approximately 35mm in length) Table 2.4 shows the comparison costs for the RP processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>LS</th>
<th>SLA</th>
<th>FDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine cost per part (euro)</td>
<td>0.52</td>
<td>3.92</td>
<td>2.64</td>
</tr>
<tr>
<td>Total cost per part (euro)</td>
<td>2.20</td>
<td>5.25</td>
<td>4.47</td>
</tr>
</tbody>
</table>

The cost per part versus the production volume for the lever part is shown in Figure 2.10. As expected, the costs for injection moulding decreased as the production volume increased by distributing the cost of the tooling. Hopkinson & Dickens (2003) found up to volumes of 6000 units, SLA and FDM are more cost effective methods for manufacture than injection moulding. LS was cost effective up to 14,000 parts. LS achieves a unit cost of approximately half that of SLA and FDM because LS allows 1056 parts per build compared to 190 and 75 parts for stereolithography and fused deposition modelling respectively. This is due to the unique ability of LS to stack items vertically in the build. The finishing of the LS parts is also much quicker than the other RM methods.
Figure 2.10: Cost comparison for lever part by different production processes (Hopkinson & Dickens, 2003)

A refined cost model by Ruffo et al. (2006a) accounts for the initial tool cost of the RM machine, therefore providing a deflection in the cost-curve at low-volume production. The model has been developed and validated using the LS process (using a 3D systems Vanguard machine), the same machine used in this project. The model calculates the cost of a build as the sum of the indirect cost associated with the time of building and the direct cost associated with the material used for manufacture. A means to express the number of parts in a build using a packing ratio has been developed (Ruffo et al., 2006a), which varies from zero in which the bed is empty to one where the volume of components in the build equals the volume of the bed. The higher the packing ratio the lower the subsequent material waste and production time per part therefore producing a cost saving. The packing ratio is defined by Equation 2.2.

\[
Pr = \frac{V_p \times n_P}{V_{beds}}
\]  

(2.2)

where \(V_p\) is the volume of part, \(n_P\) the total number of parts, and \(V_{beds}\) the total bed volume.

Part geometry was found to have an effect on the overall manufacture cost for laser-based systems Ruffo et al. (2006a). The complexity of part shapes produced increases laser scan times versus simple shapes. One significant effect on the part cost is the time costs associated with production, a comprehensive discussion of the time dependencies of the cost model is discussed in Ruffo et al. (2006b). Three key part features are identified for influencing the model process time:
• Height; directly related to the number of recoating layers required.

• Volume; directly related to the area scan process

• Bounding box volume; the minimum box for containing the part, influences area and border scanning and recoating time, can be used to identify shape complexity.

Ruffo et al. (2006b) state that the model will over-estimate cost by approximately 12%, due to measures in the model that ensure that time is not under predicted. Therefore further refinements of processes could improve costs.

A comparison of the refined cost model versus the LS and injection (IM) data from Hopkinson & Dickens (2003) was conducted. The results are shown in Figure 2.11.

![Figure 2.11: Cost comparison of level part production of the two models versus injection moulding](image)

The Ruffo et al. (2006a) model shows a deflection for low volume productions (less than 1500 parts). The part cost with the improved cost model increases to 3.36 Euros, versus the 2.20 Euros found by Hopkinson & Dickens (2003). The updated model also found that LS was cost-effective up to approximately 9000 parts (down from 14 000), at which point injection moulding becomes the more cost-effective production method. The importance of material cost was found to reduce from 78% to 33% of the total cost per part, due to the additional considerations of the refined model. The curve is not smooth as it is affected by each new row required in the x direction, each time a new vertical layer of parts is required, and each time a new bed is started. Each of these situations causes an increase of the manufacture time and the addition of indirect costs to the parts in production. As the volume of production increases the deflection due to the use of additional part layers or additional beds decreases as the curve stabilises due to the cost being split by a higher number of parts. Although other RM
processes were not evaluated, the trends of Hopkinson & Dickens (2003) are still consistent as LS allows a much higher number of parts per build.

The production costs discussed in this section are proposed to be reduced as processes and materials are being developed specifically for RM, as opposed to RP processes. There currently exists several examples of RM processes being used for high or medium-volume manufacture, which are likely to help drive profitability of the RM processes. Two examples of situations where this is the case are:

1. Hearing aids. These are manufactured in quantities of hundreds of thousands using selective laser sintering and stereolithography. These processes allow every geometry to be unique fulfilling customer requirements.

2. Pill delivery tubes. These are manufactured in volumes of about 7000 per year using fused deposition modelling, with every geometry being the same.

2.7 Discussion

The opportunity to use RM for the production of everyday items is continually increasing. This is driven by the developments in processes, materials, and research into the application of these technologies. It is important that the research into the usage of RM processes determines how RM is able to differentiate itself from conventional manufacturing and the opportunities this provides, e.g. customised products, short lead times, etc. Currently, RM appears to be the most likely method to enable customisation of sports equipment. There is, however, significant research still required regarding the material and process capabilities.
Chapter 3

Development of a structured relationship model

3.1 Introduction

This section details the processes employed to examine tennis players' perceptions of the significant grip and handle factors of rackets under play conditions. Given that the information was to be used to engineer customised grips using rapid manufacturing technologies, it was necessary to examine concepts suitable to be developed for customisation with rapid manufacturing.

The practice of concept development is a demanding process, Ulrich & Eppinger (1995) identify several discrete stages in the process:

- Identify customer needs
- Establish target specifications
- Analysis of competitive products
- Concept generation
- Concept selection
- Refinement of specifications
- Economic analysis
- Project planning

This chapter will address the issues associated with the first two points: identification of customer needs and establishment of target specifications. The goal of identifying customer needs is to understand the customer needs and communicate them effectively so they can be interpreted and used for product development. This process should yield a carefully constructed need statement, organised hierarchically (Ulrich & Eppinger, 1995). To effectively 'establish target specifications', a precise
description of what are the product’s functions is established. In this stage, customer needs are translated into more technical terms. Initial targets are developed to produce a set of product aims, and these aims are then refined as necessary as the product concept develops. Ideally each specification should possess a metric and target value for that metric. It is important that the first two stages are conducted effectively as they have lasting implications of the concept selection and development.

For the identification of customer needs, Ulrich & Eppinger (1995) discuss a methodology to comprehensively identifying customer needs. The goals of the methodology:

- Ensure that the product is focussed on customer needs
- Identify hidden needs as well as explicit needs
- Provide a fact base to justify product specifications
- Create archival record of needs activity of the development process
- Ensure no critical customer need is missed or forgotten
- Develop a common understanding of the customer needs amongst team members

The purpose of employing this methodology is to create a quality information channel between the target customers and those that influence the product (designers, engineers, etc.) so that they can interact with customers and understand the product usage. The distinction between needs and product specifications is that needs are largely independent of the product produced, whereas the specifications depend on the product concept selected and what is technically and economically feasible.

There are many methods that can be used to generate and gather raw data regarding customer needs and feelings towards products. Examples of methods include: interviews, focus groups, observation of the product in use and other variations of these concepts. The use of surveys to gather raw data is not appropriate in the initial data collection stage as they do not provide sufficient information and can become based on previous perceived needs and result in ignoring latent needs. It is important for the initial gathering of raw data that the process remains receptive to the customers information. Consequently, it was decided to develop a structured relationship model (SRM) or as it is more commonly known, a ‘feel map’. The SRM gives a diagrammatic representation of equipment factors that influence the user’s perception and how these factors interact to form the complex network that represents a player’s overall perception of a piece of equipment. The model can also provide typical player vocabulary used to describe perceptions, thus helping to increase comprehension between the designer and the player.
3.2 Previous uses

Roberts et al. (2001) first developed a formalised approach for eliciting and structuring players' descriptions of sports equipment, using qualitative methods of inquiry, and applied it to golfers' perceptions when using drivers. The techniques used in his study were in part developed from other sports based studies, which applied qualitative techniques to examine player's thoughts, feelings and perceptions (Gould et al., 1992a,b; Hanton & Jones, 1999; Scanlan et al., 1989a,b). The techniques developed by Roberts et al. (2001) have now successfully been used to develop 'feel maps' for tennis balls (Davies et al., 2003), hockey pitches (Young et al., 2005), soccer balls (McFarlane, unpublished) and golf balls (Roberts, unpublished). This approach for determining equipment factors and their relationships will be employed in this study and it has the following merits:

- Observes subject using the product.
- Allows subject to discuss characteristics that they like and dislike.
- Allows the subject to identify improvements that they would make
- The process is flexible and subject led, therefore subjects responses do not become constrained and latent needs can become expressed
- Allows the subject and interviewer the use of visual stimuli
- Provides the interviewer freedom to probe subject responses.
- Subject is able to demonstrate the product
- Non-verbal information can be reported

3.3 Methodology

The purpose of this investigation was to develop knowledge regarding players' opinions of a tennis racket grip and handle features. The structured relationship modelling technique was used to collate these responses. This was accomplished using qualitative methods, which were used to question a group of elite tennis players and coaches (n=16) under play conditions. Open-ended questions were used to probe and encourage unrestricted discussion of player perceptions in order to elicit a complete range of responses representative of a player’s experiences during a game of tennis. It was considered important that a full range of strokes were performed during the interview to ensure that perceptions that may vary between shots would be accounted for. In this investigation, L.T.A. level 3 tennis coaches were used as often as possible, due to their experience and general high standard of play. In the absence of suitably qualified players, players recommended by level 3 coaches as sufficiently
competent were used. In total 16 subjects participated in this investigation, aged 18–41 years, with a mean age 25.3 and average of over 18 years playing experience amongst the participants. Griffin & Hauser (1993) have investigated the number of subjects surveyed to reveal most of the customer needs. In two studies they found that over 90% of the customer needs were identified after 25–30 interviews. In general they believe that 10 interviews is likely to be too few and 50 interviews too many. The number of subjects was selected with this in mind and reflected the number used by Davies et al. (2003), who began to find saturation of data towards the completion of his study. Elite players were chosen as Roberts et al. (2001) believed that elite players’ sensitivity to differences in equipment characteristics increases as the player improves and gains experience. Also these elite level players generally represent what is termed ‘lead users’ who are more effective at identifying product needs (von Hippel, 1988). They are useful because they are sufficiently experienced enough to identify inadequacies or preferences with products and are often more confident with their responses than less experienced users.

3.3.1 Racket selection

Identical racket frames were used to ensure that any differences players perceived could be solely attributed to the handle/grip wrap configuration. The selected racket frame was a Dunlop 200G frame (Figure 3.1). This is a typical elite player frame and is relatively stiff with a Mid Plus head size (95 square inches).

Figure 3.1: Dunlop 200G racket frame

With the racket frame selected, the racket handles/grips were configured for the test. Eight racket frames were used in this investigation. Each of these rackets was altered by varying properties, with one racket kept as standard. This produced a range of stimuli for the players. The number of rackets was limited to eight, as a larger number would have extended test time unacceptably. Four factors were identified that could be used to alter the ‘feel’ or perception elicited by the grip wrap/handle using consultation within the project group and with a L.T.A. coach. The factors were identified as:

- Grip surface
- Handle size
• Handle shape
• Handle length

It was realised that altering the handle length could drastically alter the player's perception of the racket due to its influence on the racket's inertia characteristics. Thus only the three remaining factors were used to create the eight different configuration rackets.

**Handle Size:** There are eight common industry standard racket handle sizes (see Section 1.2.2). Typically handles are produced in sizes 2-6, with the majority of players using sizes 3 or 4. A playable range of handle sizes was selected for testing, excluding unconventional sizes 0, 1, 6, and 7.

**Grip Surface:** There is a wide range of differing grip wrap surfaces available on the market. The first stage was to select 3 completely different types of grip: a polyurethane (PU) grip, which is standard with most rackets sold today, a leather grip, and a cotton towelling grip. Overgrips, which are much thinner grip wraps that can be wound over the top of an existing racket grip, are also popular with tennis players. These were also featured on the test rackets. Three overgrips were selected: Tournagrip, the world's best selling overgrip, a Prince overgrip featuring a subtle pattern texture, and Karakal Peachy6 overgrip, a soft feeling overgrip. The overgrips were used over both leather and PU grip wraps, as it was thought that the grip used under the overgrip could influence players' perception. The remaining two grips were selected from the less conventional grips available: the Karakal Airflow plus and Groovy II. The Airflow Plus was selected because it possessed raised circular surfaces around the grip. The Groovy II was selected because it had a raised central section to the wrap with a small recessed channel through the raised section. A Rodenstock Laser stylus was used to scan the grip wrap surfaces producing the images in Figures 3.2 and 3.3. The laser stylus uses a class 1 laser (wavelength 780nm) to perform non-contact measurements with a vertical range of 0.01 μm to 600 μm. The laser has a spot diameter of 2 μm or 4 μm and can conduct 500 measurements per second. The results of the scan are interpreted in Rank Taylor Hobson's Talymap 2 software. 3D wired axonometric pictures can be produced of the scanned surface, to help further illustrate the contours of the surface profiles at any point of the surface can be produced. The Dunlop Hydramax tour and Groovy II grip could not be scanned using this method as the maximum measurable depth between the highest and lowest point is 600 μm, both these grips exceeded this distance and could therefore not be scanned.
Figure 3.2: Wired axonometric image (left) and a profile image (right) of grip surfaces scanned by Rodenstock Laser Stylus
Figure 3.3: Wired axonometric image (left) and a profile image (right) of overgrip surfaces scanned by Rodenstock Laser Stylus
Handle Shape: Handle shape was the most difficult factor to alter, primarily because it required new handles to be manufactured. Three shapes were selected, in addition to a conventional shaped racket handle. The shapes included: a typical octagonal handle shape rotated through 90° to investigate whether this would influence players perception of racket position, an ovular shape handle, mimicking handles used on original wood-framed rackets before the octagonal handle became prevalent, and a 6-sided handle; used to examine how players perceive a handle of alternative geometry resulting in the edges of the shapes sitting in different parts of their hand. The different handle shapes used are shown in Figure 3.4.

Figure 3.4: The different handle shapes used in testing (from left to right): standard handle geometry, round handle, rotated handle and six-sided handle

Handle shapes were designed using Solidworks CAD system and manufactured from Duraform PA using a 3D systems Vanguard HS machine (SLS). The RM produced handles were not found to alter the overall weight of the racket frame appreciably when compared to rackets equipped with PU foam handles. However, there was no available data regarding the damping properties of the Duraform material to compare with the damping properties of the PU foam. It is therefore impossible to speculate whether this would influence the impact perception between the two types of handle materials. The handles were designed so they could be assembled onto the existing racket shaft once the original PU foam handle was removed, as demonstrated in Figure 3.5, and were secured in place using two-part epoxy adhesive.

3.3.2 Racket configuration

One racket was kept standard with regards the grip and handle. The remaining seven rackets were varied using the discussed factors. It was necessary for some rackets to have more than one factor varied; thus rackets with significant changes did not use radical grips such as the Airflow Plus or Groovy II grip. It was considered that if there were too many changes to the grip, players may find it overly distracting and confusing to their perceptions. Scanlan et al. (1989b) commented that participant’s levels of descriptiveness can be influenced by the complexities of the perception they are
trying to describe. This was undesirable as the structured relationship modelling technique relies on players being able to articulate their perceptions of the piece of equipment. The resulting eight racket configurations are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Racket</th>
<th>Grip Wrap</th>
<th>Handle Size</th>
<th>Handle Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Karakal Groovy II Grip</td>
<td>2</td>
<td>Standard</td>
</tr>
<tr>
<td>B</td>
<td>Dunlop Hydramax Tour</td>
<td>2</td>
<td>Standard</td>
</tr>
<tr>
<td>C</td>
<td>Prince DuraTac w/ Peachy6 overgrip</td>
<td>5</td>
<td>Standard</td>
</tr>
<tr>
<td>D</td>
<td>Leather</td>
<td>N/A</td>
<td>Rotated Handle</td>
</tr>
<tr>
<td>E</td>
<td>Leather w/ Prince No Sweat overgrip</td>
<td>N/A</td>
<td>Oval</td>
</tr>
<tr>
<td>F</td>
<td>Leather w/ Tournagrip overgrip</td>
<td>N/A</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>G</td>
<td>Towelling</td>
<td>4</td>
<td>Standard</td>
</tr>
<tr>
<td>H</td>
<td>Karakal Airflow Plus</td>
<td>3</td>
<td>Standard</td>
</tr>
</tbody>
</table>

Prior to testing, each of these rackets was measured using a Babolat racket diagnostic centre (RDC) to enable comparison with the other rackets. The racket measurements are shown in Table 3.2. All the rackets were measured prior to reconfiguring the handles and an average of the measures was used for the target values when configuring the rackets, designated as the target racket in the table. Tolerances of ±10 grammes for the frame weight and ±7 kg·cm² for the swingweight MOI were specified. No tolerances for balance point were provided and the adjustment of MOI and overall racket weight took precedence as balance point was difficult to adjust without significantly affecting the other properties. Rackets D and E may appear to possess noticeably different balance point values compared to the other test rackets, however they provide swingweight values well within the required tolerance, it is therefore possible that subjects could notice a slight difference in weight distribution of these two rackets compared to the other test rackets, but these balance points would not be considered uncommon for other varieties of racket frames and therefore were considered suitable for use in this test. The tolerances correspond with a just noticeable difference level, in which 50% of subjects would...
be able to correctly predict a difference between two objects in which the properties varied by the tolerance value. This is a common procedure for determining the determinable difference between two objects and is discussed in more detail in Section 6.3.2.

<table>
<thead>
<tr>
<th>Racket</th>
<th>Weight (g)</th>
<th>Frame flex</th>
<th>Swingweight (kg·cm²)</th>
<th>Balance point (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>346</td>
<td>56</td>
<td>325</td>
<td>31.75</td>
</tr>
<tr>
<td>B</td>
<td>338</td>
<td>56</td>
<td>334</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>343</td>
<td>57</td>
<td>330</td>
<td>31</td>
</tr>
<tr>
<td>D</td>
<td>338</td>
<td>58</td>
<td>332</td>
<td>30</td>
</tr>
<tr>
<td>E</td>
<td>338</td>
<td>57</td>
<td>323</td>
<td>30</td>
</tr>
<tr>
<td>F</td>
<td>338</td>
<td>56</td>
<td>327</td>
<td>31.5</td>
</tr>
<tr>
<td>G</td>
<td>346</td>
<td>55</td>
<td>330</td>
<td>31.25</td>
</tr>
<tr>
<td>H</td>
<td>350</td>
<td>58</td>
<td>326</td>
<td>31.25</td>
</tr>
<tr>
<td>Target</td>
<td>341</td>
<td>56</td>
<td>330</td>
<td>32</td>
</tr>
</tbody>
</table>

3.3.3 Court preparation

All testing was conducted on indoor acrylic-surfaced hard courts. This surface was used because most academies employing the test coaches possessed these facilities. The second advantage of indoor courts is that there was no concern about atmospheric condition or environmental factors influencing the measurement equipment. In each test, the players were provided with nine new Slazenger Wimbledon High Vis balls, ensuring ball conditions were consistent for all players tested.

3.3.4 Interview procedure

To enable the creation of a structured relationship model of tennis racket grip/handle factors, players perceptions of the equipment were elicited and recorded. The player’s responses were extracted using open-ended questions, which have a number of advantages. They are flexible; they allow the interviewer to probe, so that he may go into more depth if they choose to, or clear up any misunderstandings; they enable the interviewer to test the limits of the respondent’s knowledge; they encourage co-operation and help to establish a rapport; and they allow the interviewer to make a truer assessment of what the respondent really believes. Open-ended situations can also result in unexpected or unanticipated answers which may suggest new relationships or hypotheses (Cohen & Manion, 1980). The use of open ended questions allows the probing of the player’s responses, whilst minimising the possibility of influencing or leading the player’s responses. To aid the interviewer, an interview guide (see Appendix A) was prepared to help structure the interview. The interviewer used these questions to probe the responses following each play period. An example of an open-ended question and probed
Interviewer: "How did you find the feel of that handle?"

Player 16: "I didn't like this one at all, I didn't like the way it sat in your hand, just sits very uncomfortably, because it sticks in your hand there"

In order to clarify this sentence the interviewer could use the following elaboration probe:

Interviewer: "Can you explain what you mean by sticking in your hand?"

The interview guide also provided a space for the interviewer to note descriptors or key-words used by the subjects which could be used to help probe the subject. An example can be seen below:

"The texture of the grip is pretty good, feels quite nice and its tacky which I like, don't know how it would go after using it for a while though, think it would become smooth"

The interviewer could probe the quote, by asking:

"What do you mean by tacky?"

To conclude the test, a set series of questions were included on the interview guide, which investigated the level of the player's experience, their general racket/grip preferences, and their experience of the test procedure. All conversations between interviewers and players were recorded to ensure that no information was missed or lost and that the interviewer could concentrate fully on probing the subject. Every player and interviewer tested was asked to wear a wireless lapel microphone. The microphones fed into small radio transmitters that could be attached to the player's belt or be carried in the pocket. The radio transmitters broadcast on two separate frequencies (UHF radio and VHF radio) to ensure that the recordings did not interfere with each other. The radio transmitters fed into a receiving station where the conversations between each pair (interviewer and subject) were recorded onto minidisk. The recordings were made in stereo so that each microphone signal was recorded on different channels, a separate channel for interviewer and subject. This enables easier transcription, since frequently interviewer and player would talk at the same time. The players were not interviewed during play, as it was difficult to communicate due to the distances between player and interviewer and the need for players to concentrate on the equipment they were using. Players were encouraged to make any comments they felt necessary about the rackets during play as these could be recorded in the transcription process. None of the players tested found the recording equipment invasive or prohibitive to them during the course of the testing.
3.3.5 Test protocol

The test was designed to examine a broad range of players strokes, so that players perceptions were as representative of the demands of tennis as possible. Work by Davies et al. (2003) had investigated several methods to explore the range of player's strokes for testing to produce an SRM. His work suggested that a normal warm-up routine was the most suitable; as players perform most of the major tennis strokes, typically starting the routine with groundstrokes (backhand and forehand) from the back of the court, before coming to the net to practise volleys and smashes. The routine finishes with both players practising their serve. The advantages of this routine are that players are familiar with it and it only takes approximately 5 minutes to complete. A short routine was also desirable as there was a need to maximise the number of rackets that the players would use during the course of the test whilst minimising potential player boredom and fatigue. It was decided that the entire test should last no longer than one hour per player including the interviews. An initial five-minute warm-up with the players own racket ensured that all subjects were prepared for the test and that they were able to rehearse the shots to be conducted prior to the test commencing. As each racket test routine lasted approximately 5 minutes, 6 racket tests were conducted per player allowing sufficient time for the interviews after each test with the player. Pilot tests showed that within five minutes players were able to establish perceptions of the tests rackets, thus the five minute test period was considered adequate. The only concern with a short duration period was that racket grip wrap and handle factors influenced by longer duration periods of usage i.e. grip wear, could not be observed using short test periods. However, the demands of test estimated at approximately 1 hour per racket, was considered unfeasible for this type of test when using same number of test subjects as intended for the shorter duration test. The players were tested in pairs to use the warm-up routine method and to maximise the number of subjects tested in the study. The rackets were randomly assigned to players using a modified Latin square (Table 3.3). Since players were tested in pairs, this ensured that although each player only used six rackets each pair would use all eight rackets in their test.

Summary of protocol

- Players briefed about test procedure and signed consent obtained. Questions answered.
- Players allowed to warm-up and hit shots with their own racket.
- Recording equipment placed on subject.
- First assigned racket given to player. Standard five-minute warm up completed.
- After 5-minute warm-up player returns to assigned interviewer to discusses their perceptions.
- Players given next assigned rackets.
- Test repeated until each player has used all six of their assigned rackets.
- Players answer experience questions.
- Players debriefed and recording stopped.

Table 3.3: Latin square of player test racket order

<table>
<thead>
<tr>
<th>Subject</th>
<th>Racket number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>E</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
</tr>
<tr>
<td>5</td>
<td>H</td>
</tr>
<tr>
<td>6</td>
<td>G</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
</tr>
<tr>
<td>8</td>
<td>A</td>
</tr>
</tbody>
</table>

3.4 Content analysis

Content analysis is the process by which raw data is organised into interpretable and meaningful themes and categories (Scanlan et al., 1989a). In this investigation, the transcriptions from the player interviews provided the data and the quotes for the content analysis. The basic units of analysis were quotes from the transcriptions. Each quote was 'a statement made by the subject, which is self-definable and self-delimiting in the expression of a single, recognisable aspect of the subject's experience' (Cloonan, 1971). The quotes in this work varied from a word up to a paragraph in length. There exists two approaches to content analysis; the inductive or deductive approach. The deductive approach uses pre-determined themes and categories to organise the quotes, whereas the inductive approach allows themes and categories to emerge from the quotes (Patton, 1990). The inductive approach was previously employed by several qualitative sports researchers (Davies et al., 2003; Gould et al., 1992a,b; Hanton & Jones, 1999; Roberts et al., 2001), and was used in this investigation. The first stage of this process is to cluster the quotes around underlying uniformities (Glazer & Strauss, 1967). The underlying uniformities, or common threads, are the emergent themes. 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 (Patton, 1990). In this study 16 interviews produced 64 pages of transcriptions; these were analysed and resulted in 2280 quotes, which clustered into 54 themes, the number of actual individual quotes identified is lower as some quotes were clustered into more than one theme. QSR NUDIST software was used to cluster the data, to allow coding of text documents into suitable clusters or nodes. NUDIST allows searching between
nodes so that relationships between the coded data can be identified. Figure 3.6 illustrates how quotes are clustered into the lowest level theme.

"It also feels the same all the way round as well there's not much shape to it so it just feels..."
"It was very different cause its kind of much more circular as opposed to having your little ridges"
"The grips are robust and there are so many angles on them that you just don't know where to put your hand, it's on a ridge"
"Too fat, I think it's the shape cause it's hexagonal its more sides to it, less control as well."
"More conventional grip almost like a Head racket actually quite a long flat part grips..."

"I think that like the feel sharp underneath it might even be lengths of the the hexagonals that are different"
"...the last racket was that the bevels were well defined...which I quite liked it wasn't round...I think that it would take me a little bit to get used to because it's a lot different from one I have ever tried in the past with much bevels"
"I don't like it when its round but this one is it feels...rectangular and slim so I don't like that...there's no bevels so when I hit the ball I feel as though it's going to spin in my hand so it's slightly miss hit the racket turns round"
"...the racket handles get ridges on so you can sort of feel the change of your grip when you go from eastern to western and with the towelling being quite not even and not smooth its kind of hard it sort of feels strange in your hand cause your hands sort of get used to be feel and like smooth grip and the towelling I don't know just the unevenness of it is quite hard to do you know sort of on some grip you get a groove that runs every right round this one sort of like clogs up in places and that makes it hard"

"As you were swinging through so you felt as though your hand was probably slipping on the end a little bit...I think it would do with being a little bit wider at the bottom."
"the biggest thing for me didn't have like a heel on the but so I really felt loose at the bottom of the racket almost like it would come out of the hand"
"...it feels as if the handle smaller at the bottom than it is at the top so it forces your hand down and then, so your rackets are slipping"
"bottom of the handle almost certain that its smaller than the top of the handle, makes it feel slippy"

Figure 3.6: The process of clustering quotes into higher order themes

From the raw data, all themes are further clustered into higher level themes until they become general dimensions. At this point they can be clustered no further and have become a general grouping for a wide range of quotes. Using this approach, Roberts et al. (2001) discovered ten general dimensions of feel for a golf driver; Davies et al. (2003) discovered eight general dimensions of feel when investigating tennis balls. The clustering of quotes up to general dimension is illustrated in Figure 3.7. Not all quotes cluster down to the raw data theme (the lowest level). This occurs when quotes differ in their levels of descriptiveness. This can be caused by the subjects' ability to articulate their answers and the complexity of the perception. Greater description occurs with more articulate subjects and complex multifaceted perceptions (Scanlan et al., 1989b). Those themes that involve less description do not always carry through all inductive levels and therefore immediately become a higher inductive level.

The inductive building process is iterative. Many iterations comparing and contrasting quotes and categories are required to create themes that accurately reflect the subjects' perceptions of the grip and handle. The guidelines for forming themes, created by Patton (1990), is described by the following. Firstly, each individual theme, regardless of level of analysis, is inclusive. An inclusive theme adequately captures the clustering of lower order themes that comprise it. Secondly, all themes within a given level of analysis are distinct from each other. Thirdly, a higher level of analysis captures
most of the lower order themes, leaving as few unclustered themes as possible. Remaining unclustered themes are either disregarded if undistinguishable or retained if important.
Figure 3.7: A complete tree structure demonstrating clustering of range of quote to form a general dimension
3.5 Creation of structured relationship model

Roberts et al. (2001) and Davies et al. (2003) further developed the tree structures to produce a structured relationship model. The resulting structured relationship model for this investigation is shown in Figure 3.8, with a larger version in Appendix 3.7. Each level of the data structure is colour coded to distinguish them. The tree structures produced by the inductive building process and their related themes were used to produce a diagrammatic representation of the tree structure, in which the general dimension (black text) forms the hub of the diagram, and each lower order theme forms the next level on the diagram: high order theme (red text), high order sub-theme (blue text), raw data theme (green text). Useful descriptors or vocabulary from the data themes are also included (orange text). Representing the tree structures in this way permits all of the general dimensions to fit onto one diagram. It is then possible to begin identifying inter-dimensional relationships (grey text). The identification of overlapping themes/dimensions occurs by identifying quotes that have been coded into two nodes, or quotes in one theme that in the context of the transcript were amongst quotes from another theme. This ultimately helps to identify possible relationships in players perception between the different themes/dimensions.
Figure 3.8: Structured relationship model of tennis racket handle
3.6 Validation of structured relationship model

The production of a structured relationship model identifies only the factors that players perceive to influence their feel. The technique does not allow the identification of the relative importance of each of the dimensions. Therefore this model alone is only representative of the sample of players interviewed in the testing. To validate the SRM, and therefore attribute its findings to a much larger population, a questionnaire was produced and distributed to a significantly larger group of tennis players, investigating the importance of the factors identified in the SRM. This method of validation has previously been accomplished using a postal questionnaire (Roberts, 2002). It was decided for this investigation to use an internet-based survey. The use of the internet improves the effectiveness of data collation as the responses need not be input again as they can be saved direct into a file for analysis, improving data accuracy and efficiency. A copy of the questionnaire used can be seen in Appendix B. A numbered scale was used for participants to complete their responses. This method is popular because it is familiar to respondents and allows the direct production of scaled values. Sufficient points were used so that the participants could accurately rate their preferences, without having to force their responses into the nearest available category. Bass et al. (1974) suggest that a maximum of nine points can be used effectively. Ten-point (or higher) scales are rarely used as it is difficult for observers to make distinctions finer than a 10-point scale requires. The scale was oriented using descriptive words at each of the extremes. These words were typically selected from descriptors highlighted in the structured relationship model or analysis of transcripts used to create the model. An example of a scaled-response question can be seen in Figure 3.9.

**How influential is the wrap material on the grip your hand makes on the racket?**

<table>
<thead>
<tr>
<th>No influence</th>
<th>Extremely influential</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.9: Example of scaled response question

The questionnaire was split into six sections. The first two sections concerned personal information about the respondent, their playing, and coaching experience. Equipment usage was also investigated including rackets used, grips used, how often grip wraps were changed, and whether vibration devices were used. Sections 3-5 of the questionnaire investigated the feeling from an 'ideal' forehand, backhand and serve respectively. As the feelings from these shots had been described separately in the formation
of the SRM it was necessary to investigate whether players anticipated different responses for each type of shot. The majority of the questions in these sections concerned the impact perceptions dimension. The sixth section examined the handle and grip configuration, investigating handle surface, grip factors, and in-game gripping dimensions. Determining the importance of all factors identified by the SRM was not feasible due to a number of reasons. First, it was difficult to appropriately phrase questions regarding some of the factors identified in the SRM. Second, themes such as handle shape were stimulated in the players tested to produce the SRM using different handle shape rackets. Without this stimulation, the influence of handle shape may not be apparent to many players and therefore they would find any questions regarding the handle shape irrelevant or confusing.

A broad audience was selected for the questionnaire. To accomplish this, email addresses of coaches and tennis clubs were gathered and an email with a hyperlink to the questionnaire was circulated to 717 addresses. Over a 2 month period, 117 people responded to the questionnaire. The mean age of the respondents was 37.8 with ages ranging from 13-69 years. The amount of tennis playing experience ranged from 1-55 years, with a mean amount of 23.7 years, 23% of the respondents possessing some form of coaching qualification. The subjects participated in tennis on average 2.4 times a week.

3.6.1 Questionnaire results

The following sections will discuss the results provided by the questionnaire responses, they are split into two sections discussing responses to feel of an ‘ideal’ tennis stroke (forehand, backhand and serve) and the relative importance of the various racket characteristics. Each of these questions sections will discuss the results for the questions posed within the section, to attempt to identify common trends in the subject responses which may be useful for future concept development.

3.6.2 The feel of an ‘ideal’ tennis stroke...

How much effort would you expect to execute the shot? (Range: Minimum effort – Shot hardwork) (Figure 3.10a) The ideal effort level for a forehand and backhand is perceived to be neither effortless nor hardwork, with players providing a mean rating of 5.27 and 5.33 respectively. The serve has a higher expected effort level, which could be anticipated due to nature of the stroke, with a mean rating of 6.22. 65% of players rated the effort expected to execute the serve as rating 7 or more. This is due to a large number of respondents providing a rating of 8, suggesting that there is a sufficient level of agreement between subjects regarding a high level of effort required to execute a serve. The standard deviations of the forehand, backhand and serve rankings of 1.56, 1.71 and 1.92, respectively show that there is some variability in shot effort amongst individuals, although the forehand has the most agreement amongst the participants.
How would you expect the 'impact' to feel in your hands? (Range: Dead – Lively) (Figure 3.10b) The forehand, backhand and serve were rated similarly with average scaled responses of 5.27, 5.16 and 5.55 respectively. This suggests that players expect the impact to be neither dead nor lively in feeling. The standard deviations of 1.89, 1.84 and 1.97 for forehand, backhand and serve respectively, suggest that the preference again varies for each individual, although players predominantly like the feel to lie between 3-7 on the scale.

How much vibration would you expect to 'feel' at impact? (Range: No vibration – Lots of vibration) (Figure 3.10c) The ideal vibration at impact is low with mean values of 2.53, 2.7 and 2.92 respectively. Each of the 3 shot types had between 85 and 73% of their ratings below 3 on the rating scale. The standard deviation of 1.2 suggests good agreement on the amount of vibration for this stroke, but values of 2.37 and 2.33 for backhand and serve respectively indicate that there is some personal preference in the vibration levels for these shots.

How should the racket weight feel during the stroke? (Range: Light – Heavy) (Figure 3.10d) Players mean responses for the forehand, backhand and serve were 3.90, 4.00 and 4.17 respectively, indicating that participants preferred the racket to be neither light nor heavy. Players showed a slight tendency to a lighter feeling racket. This would be expected as descriptors such as light and heavy are normally used when an item is deviating from the players’ ideal weight. The standard deviations showed some individual differences for the forehand (1.59) and backhand (1.58) with more considerable individual differences for the serve (1.82)
(a) Responses to 'how much effort would you expect to execute the shot?'

(b) Responses to 'how would you expect the impact to 'feel' in your hands?'

(c) Responses to 'how much vibration would you expect to 'feel' at impact?'

(d) Responses to 'how should the racket weight 'feel' during the stroke?'

Figure 3.10: Charts for responses to 'feel' of an ideal tennis stroke
Ranking of grip wrap characteristics in order of importance on the grip wrap used with the player’s racket. (Figure 3.11) Examining the three in-play grip characteristics (absorbency of wrap material, durability of wrap material and how well wrap attaches to handle), it was evident that the absorbency was the most important grip wrap factor of the players questioned. 40% of players selected absorbency as their most important factor, 10% more than durability and the adhesion properties of the grip wrap. The second most important characteristic was equally spread amongst all three properties and the least important characteristic was clearly the adhesion property of the grip with 47% of participants selecting it as the least important. Other important characteristics suggested by participants included the thickness of the grip, the colour of the grip and the ‘tackiness’ or how sticky the grip surface was.

![Ranking of in-play grip characteristics](image)

Figure 3.11: Ranking of in-play grip characteristics responses

How do you prefer your grip surface to feel? (Figure 3.12)

The grip surface showed an average scaled response of 5.19, suggesting that the participants prefer neither a totally smooth grip nor a totally textured grip. However a standard deviation in the responses of 2.4 suggests that the preferred grip surface is a matter of much inter-individual variability.

How influential is the wrap material on the grip your hand makes on the racket? (Figure 3.13) Again the importance of the grip wrap is exhibited by the responses to this question. The average scaled response for this question was 7.07, while a standard deviation value of 1.91 suggests there is variability amongst the participants. Over 75% of the players selected a value of 7 or more,
suggesting that players find the grip surface influential to the quality of grip their hand makes with the racket.

**How much does the wrap surface/texture influence your transition between different grips when making shots?**  (Figure 3.14) Players felt neither influenced heavily nor un-influenced by the grip surface, with a relatively large standard deviation of 2.51 again suggesting that the amount of influence is a very individual perception. However, 30% of the participants did rate the influence of the grip and grip transition at a value of 7.

**Importance of grip factors when gripping the racket**  (Figure 3.15)  
Players generally selected the fit of the handle in the fingers and fit of handle in the palm of the hand as the most important factors when gripping the racket, with over 75% of the participants selecting these factors as the most important. The fit in the palm of the hand was marginally more important, polling 10% more responses. Clearly both these factors are important to players as they also rank highly as the second most important factor when gripping the racket. The least important factors selected by the participants were the handle buttcap size and width across the grip, with over 60% of the participants nominating these factors as the least important to them when gripping the racket. The remaining factor, the definition of handle edges/bevels the responses suggest that players acknowledge that they are influenced by the definition of the handle edges, but are more influenced by the fit of the handle in the fingers and palm.

**Words that correspond to feelings that you like to experience from your racket grip?**  (See Figure 3.16) Examining the words that correspond to feelings elicited by the grip showed the three most popular feelings amongst the participants to be Dry (18.7%), Smooth (14.84%) and Spongy (14.84%); the least popular of the feelings included on the questionnaire were Peachy (2.58%), Plasticy (1.94%) and Silky (0.65%). Figure 3.16 shows that in general these feelings are perceived to be important.
How do you prefer your grip surface to feel?

How important is the feel of the grip surface to you?

Figure 3.12: Responses to 'how do you prefer your grip surface to feel?'
How influential is the wrap material on the grip your hand makes on the racket?

Figure 3.13: Responses to 'how influential is the wrap material on the grip your hand makes on the racket?'

How much does the wrap surface/texture influence your transition between different grips when making shots?

Figure 3.14: Responses to 'how much does the wrap surface/texture influence your transition between different grips when making shots?'
Player rated grip factors by order of importance when gripping the racket

Importance rating (1 = most important - 5 = least important)

Figure 3.15: Responses to importance of grip factors when gripping a racket
Feelings players like to experience from the racket grip
(could choose more than one factor each)

How important are these grip feelings to you?

Figure 3.16: Responses to grip feelings players like to experience
3.6.3 Relative importance

Table 3.4 shows the average scaled response values for all the importance questions posed in the questionnaire. The spread of the responses amongst the participants is indicated with their respective charts in Figures 3.10, 3.12 and 3.16. The table also expresses the standard deviation of the responses. The feel of the grip surface and the feelings elicited by it are of highest relative importance to the participants. The racket weight is shown to be the second most important factor on influencing an 'ideal' shot. The least important factor is the impact vibration of a serve and the backhand. However, it is worth noting that the standard deviation of the importance of impact vibration question is the highest, suggesting that the responses to this were varied. The mode value is reported to help highlight these variations by providing the most frequently used values, where in the case of the question regarding the importance of forehand impact vibration the average rating is 5.51, but over 25% of respondents provided a response value of 7 for this questions, suggesting that for some players this factors is particularly important.

Table 3.4: Relative importance of each characteristic

<table>
<thead>
<tr>
<th>Question</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Importance of feel of the grip surface</td>
<td>7.37</td>
<td>1.80</td>
<td>9</td>
</tr>
<tr>
<td>Importance of selected grip feelings</td>
<td>7.08</td>
<td>1.83</td>
<td>9</td>
</tr>
<tr>
<td>Importance of feel of the grip surface</td>
<td>6.38</td>
<td>1.58</td>
<td>7</td>
</tr>
<tr>
<td>Importance of feel of the grip surface</td>
<td>6.34</td>
<td>1.98</td>
<td>6, 7</td>
</tr>
<tr>
<td>Importance of feel of the grip surface</td>
<td>6.30</td>
<td>1.52</td>
<td>5, 7</td>
</tr>
<tr>
<td>Importance of effort - Serve</td>
<td>6.22</td>
<td>1.94</td>
<td>5</td>
</tr>
<tr>
<td>Importance of feel - Serve</td>
<td>6.13</td>
<td>1.57</td>
<td>6</td>
</tr>
<tr>
<td>Importance of feel - FH</td>
<td>6.06</td>
<td>1.78</td>
<td>6</td>
</tr>
<tr>
<td>Importance of feel - BH</td>
<td>5.95</td>
<td>1.65</td>
<td>5</td>
</tr>
<tr>
<td>Importance of effort - BH</td>
<td>5.56</td>
<td>1.80</td>
<td>7</td>
</tr>
<tr>
<td>Importance of effort - BH</td>
<td>5.52</td>
<td>2.36</td>
<td>7</td>
</tr>
<tr>
<td>Importance of effort - FH</td>
<td>5.51</td>
<td>2.20</td>
<td>7</td>
</tr>
<tr>
<td>Importance of impact vibration - BH</td>
<td>5.48</td>
<td>2.37</td>
<td>5, 6</td>
</tr>
<tr>
<td>Importance of impact vibration - Serve</td>
<td>5.43</td>
<td>2.35</td>
<td>3, 7</td>
</tr>
</tbody>
</table>
3.7 Discussion

A structured relationship modelling technique has been used to establish factors that influence a player's perception of a tennis racket handle and grip. Four general dimensions have been identified (grip factors, handle surface, in-game gripping and impact perceptions). The use of this model is valuable as it identifies not only factors of the handle and grip that influence a player's perception, but some of the vocabulary used by players to describe the sensations received from the documented factors. The model has also helped to determine the possible influences on perception that could be caused by altering racket handle designs. For example, the inter-dimensional relationships identified that by increasing handle width, players perceive the racket to have an effect on racket power. The application of a large scale questionnaire using information gained from the structured relationship model has further increased understanding of the influences on the player through the racket handle.

One area which was highlighted as particularly important by this method was the importance of the grip surface on comfort and performance. Other useful trends highlighted by the questionnaire demonstrate that whilst there are some general trends players may follow, there are also many factors in which player's preferences differ considerably. Examples of this can be seen in the wide range of variability over the importance of vibration or the type of grip surface the players like to use. These differences may be attributed to level of experience, style of the player's game or purely personal preference. This, establishes that customisation is a valuable concept when applied to tennis, as players' ideal sensations are obviously wide ranging. Customisation may be necessary to deliver the equipment necessary to improve individual comfort and performance.

However, there are some drawbacks in using the model. The nature of the test was designed to represent play conditions as effectively as possible. However, the compromise between testing as many rackets as possible using a test of suitable length meant that players were only able to spend five minutes with each racket. This was a concern, as some players suggested that the properties of the grip may change more dramatically, when in use for a longer duration. Effects such as grip wear, durability and sweat absorption or response to sweat were therefore not observed as effectively as they could have been.

The work by Roberts et al. (2001) on golf clubs and Statham (TBC) on tennis rackets identify the grip or handle of the equipment as one general dimension on their respective structured relationship models. In this study, the grip/handle dimension has been specifically analysed to create four general dimensions. The themes and dimensions identified have become less self-defined and smaller in number than previous studies, due to the fact that the area of interest is much narrower than those previously investigated.

One of the issues identified with developing a questionnaire from the structured relationship model work, was that players in the study commented that typically during a game they thought infrequently
about their grip and the interaction between it and their hand. This was overcome in the player testing by designing the rackets and grips to stimulate responses from the players and questioning them specifically regarding the grip. However, this issue could have been problematic in the use of the questionnaire as there is no way to stimulate the respondent to think about their grip interaction and the perceptions it produces. Examples of this can be observed with factors that were considered least important by the internet questionnaire: grip size, grip shape, and feeling of vibration from impact. These factors were perhaps not ideal for representation by an internet questionnaire due to the nature of the sensations produced by them. For example, it is difficult for a respondent to consider the effects of a different shaped handle or a significantly vibrating racket, without physically experiencing the stimuli.

Among the key findings observed in the content analysis are that many of the players felt that the six-sided handle had more sides than a conventional handle although it actually has two less. This is thought to be due to the fact that the six-sided shape placed handle edges in an unfamiliar position in the players' hand. It was also observed that competent players barely look at the racket when they play shots and rely on their hand's tactile feedback to establish the position of the racket face. This means that when equipped with unconventional shapes or highly textured grip surfaces their perception of the handle shape and racket position are influenced and players find it difficult to make adjustments to their grip for specific shots. A conventional 8 sided shape enables positioning of the racket for flat and slice shots. Typically they expect the handle shape to be wider in line with the frame and narrower in line with the impact direction. The role of vibration in players' perceptions of shots was highlighted as a key influence. Players expect to experience a certain amount of vibration, but too much can result in player discomfort and players being unable to 'feel' the ball on the strings. Too little vibration results in players unable to 'feel' the ball on the racket. The majority of players felt that by being unable to feel the ball on the racket, their control was compromised.

The shape of the handle also influenced the feel of impact due to different distribution of impact forces experienced in different parts of the hand compared to standard handle shapes.

Players' selection of their grip material is much more influenced by personal preference, with no obvious general trends emerging. This explains the vast range of grips available. However, some key factors in a player's decision for grip were identified. The first major influence is how much a player sweats whilst playing tennis. Players that sweat tend to prefer absorbent grips as they were concerned about losing grip traction the longer the game progressed. Some players were also concerned about how the grip behaved once it had absorbed sweat as they wanted to ensure that the properties remained consistent from perspective of performance, cost and frequency of replacing the grip. The grip force is also an influencing factor with lighter gripping players tending to like the tacky grips. Players that gripped tighter still noticed the tackiness, but were less concerned by its effect on their
performance. Players did comment on how grip material could influence shots played by the players either by preventing them from selecting the appropriate shot quickly enough or due to the fact that they couldn't adjust their grip for the shot due to the confusion caused by the grip surface. A player's selection of racket handle size could be seen to be a compromise, as several players suggested that they preferred larger handles for serving but found that they were more restrictive when used for groundstrokes as it inhibited wrist movement. Several players also commented that larger handles made the rackets feel more powerful, but they felt that they compromised control in their shots as a result.

The initial intention of employing the structured relationship modelling techniques was to develop a statement of product needs and a list of target specifications. Essentially, this process has been able to determine the product needs by identifying factors of the racket handle or grip wrap that players are influenced by. Any grip wrap or handle factors not discussed or identified by this process can be considered insignificant. However, due to a lack of previous research it is not possible to determine target specifications for each of these factors identified, therefore further work must be employed to identify the target specifications for each of the factors as required. Depending on the concept to be developed not all factors will need to be investigated and only those in direct relation to the actual concept to be developed need to be determined.
- Moisture absorption
- Hand cooling

These six areas were developed into six different concept approaches, each relating to at least one of these areas. A brainstorm of the concept areas is shown in Figure 4.1.

Given the novel approach of using RM in tennis racket handles, a concept was initially developed addressing only one of the concept factors. Different concept factors were evaluated and the three weakest removed so that further development of the stronger concepts could be conducted before final selection. The rejected concepts were grip shape, grip size and grip texture. Grip shape was rejected because work during the structured relationship model had shown that players are familiar with specific grip shapes from an early age. Typically they do not like to deviate from their preferred handle shape. There were also concerns over the value of modifying the racket handle, when player testimony suggested that the handle would have to remain an eight sided shape. The grip size was rejected, because cheaper options exist for players to modify the size of their racket handles. These methods are predominantly used to increase the handle size, by using a variety of different tapes and wraps. The need of a rapid manufacturing system to customise player's handle size was considered to be of little value, as well as potentially confusing to players who are familiar with standard handle sizes. The final concept of grip texture was rejected, even though there existed significant interest from players and significant potential in design. Since the available RM materials and processes were not at a sufficiently advanced state, this research could not be effectively undertaken at the current time. The remaining three design features were further analysed and several concepts were developed to determine the project direction. The capabilities of RM processes were examined to ensure that the production of the selected concept would be achieved with present systems. The value of each concept was assessed from revision of structured relationship model transcripts and discussions with individuals involved in either tennis coaching or racket manufacture. The brainstorm showing the three developed concept areas, with the main concept ideas for each one shown in Figure 4.2.
Figure 4.1: Brainstorm of initial handle concepts
Porous nature of SLS polymers could be used to produce wicking action in the part to draw sweat away from the surface. This was influenced by varying densities.

Holes situated perpendicular to direction of airflow cause pressure drop which draws air from through holes in the handle.

Variable density sintered material

By altering the density of the handle, using functionally graded materials or adding variable amounts of damping material it may be possible to produce a bespoke vibration reducing part.

Springs (or similar arrangements) can be used to damp vibrations and each spring element can be individually customised as required.

Holes in racket frame facing airflow force higher pressure air from racket swing into the racket frame and out of holes in handle.

Figure 4.2: Refined brainstorm of handle concepts, with selected concepts illustrated.
Of the three concepts, the vibration/impact reducing concept was selected as the most appropriate for development in this project. It was believed that this concept offered the most opportunity for individual customisation, as well as developed a product of significant interest to players for injury reduction and comfort. Furthermore, the ability for the SLS RM processes to produce springs and similar arrangements in closed volumes had previously been prototyped, which reduced concerns over whether manufacturing of the concept could be achieved. Both the airflow cooling and moisture wicking handle concepts were of interest, unfortunately concerns existed whether they would yield significant results. However, it is envisaged that future development of SLS parts of a semi-porous nature provides an attractive concept for moisture control of sports equipment handles.

For vibration damping technologies, the SRM identified that there was considerable player concern over the vibration received at impact. However, the characteristics of the vibration players prefer or dislike have not been fully established and investigation is required to define the vibration phenomena from ball impacts that are of interest to players of varying ability levels.

In conventional product design, benchmarking tests are frequently conducted to determine the effectiveness of existing products and to assess the advantages afforded by novel concepts. In this thesis the production of the racket concept as a prototype will be developed to ensure that it performs effectively and will be compared with the results of a conventional racket. The developed concept cannot be directly compared against existing vibration reducing racket technologies, due to the frame property dependencies of many of the technologies. Future comparison of the performance of the concept versus other various racket technologies may be conducted upon completion of successful testing.

### 4.3 Definition of handle concept

In this thesis the handle has been selected as the racket feature for development. The selected concept area aims to develop a handle that uses spring or spring-type elements to modify the vibration transmitted to the users. The spring elements will be designed so that future development of the handle concept will allow optimisation and individual customisation of the elements as required. The handle has been developed to be manufactured wholly by one or a combination of RM processes such that it can be integrated onto a conventionally manufactured racket frame.

### 4.4 Summary of previous developments

A patent search was conducted to investigate prior art in sprung-type handle concepts. A brief synopsis of competitive patents is discussed in this section. The patents are ordered chronologically to illustrate how the approaches have changed.
The earliest of the relevant handle concepts was Newbery (1955), which uses a metal leaf springs in the handle of a sporting implement to produce greater handle strength and to provide the implement with quicker return and better resilience upon striking the ball (Figure 4.3a). The first dynamic vibration damping racket innovation was created by Lacoste (1976). The concept is constructed using an elongated section of elastomeric material. One end of this section is attached rigidly to the racket at the point of an anti-node and the other end is allowed to vibrate in free space, therefore dissipating the energy from impact and reducing the amount of vibration transmitted to the player. The dimensions of the member are adjusted so that the natural frequency of the vibration of the member corresponds with the vibration frequency induced by striking the implement. A related concept by Kubokawa (1983) demonstrates a handle for industrial tools, such as a disk grinder (Figure 4.3b). A pair of metal coils (small and large diameter) are positioned around a fixed axle attached to the tool. The user grips the tool with their hand contacting the springs. These springs are claimed to aid in the isolation of the subject’s grip from the transmitted tool vibration. Adam (1987), proposed a racket handle sleeve using internal spring elements to permit greater tolerances between the handle shaft and grip sleeve (Figure 4.3c). The spring elements deform against the handle shaft to provide a good fixing and positioning of the handle. In addition, the spring elements help to reduce effects such as rebounding between the handle sleeve and handle shaft. These movements can be both uncomfortable and annoying to the player as well as damaging to the handle sleeve. The device produced by Takatsu & Hariguchi (1989) incorporates a mass supported by visco-elastic material (Figure 4.3d). Impact causes deformation of the visco-elastic material, displacing the mass. It is claimed that this arrangement can be tuned to match and attenuate different vibration characteristics. This is a similar concept to Lacoste (1976).

Two similar patents were discovered for concepts addressing off-centre impacts, (Henry, 1993; Walkhoff, 1989) (Figures 4.3e, f). In both these patents, the handle is formed of a separate handle outer shell and inner shaft sections. The inner shaft is connected to the rest of the racket frame. Damping elements are positioned between the two handle sections to allow limited rotation of the racket head about the longitudinal axis of the racket. The elements allow this rotation whilst the handle outer remains in it’s neutral position. Both of these concepts claim to primarily exert influence for off-centre impacts with little or no effects on off-centre impacts. The handle structure is completely redesigned in a concept from Hsich (1999). In this patent, a combination of grooves and solid blocks are used to produce the handle and rubber pads are placed between the grooves (Figure 4.3g). The interaction between the grooves and solid blocks at impact is claimed to reduce vibration transmission. Another dynamic vibration damping concept is provided by Lammer (1999). In this concept a vibration dampening unit is located in the buttcap of the handle. The unit contains a weight suspended by elastomer, allowing the weight to move freely in all directions to attenuate some of the vibration.
energy from impact. This concept is a more elegant approach to the concepts of Lacoste (1976); Takatsuka & Hariguchi (1989). The last of the notable concepts is Severa et al. (2002), who describes a racket with separate racket head and handle portions to reduce transmitted vibrations. A vibration absorbing material (rubber) is disposed between the two portions to reduce the transmitted vibration (Figure 4.3h).

Of the concepts identified only those concepts described by Adam (1987) and Hsich (1999) were considered to be achievable using current RM processes. Processes such as LS would allow part consolidation to be implemented to produce these concepts in one piece as well as the potential of customising the performance of each of the concepts as required. The other concepts were either unsuitable for RM processes due to being outdated concepts e.g. Newbery (1955) or because the concept requires several materials to be used in the assembly and therefore negates the advantages of RM e.g. Lacoste (1976), Henry (1993).

A number of other vibration concepts were identified and analysed, such as the Head intellifibre technology as discussed by Kotze et al. (2003). These are not discussed in this section, as it was of most relevance to discuss the patents solely related to sprung or vibration damping handles instead of general vibration damping technologies that exist, of which there is a vast range of possibilities.
(a) Earliest handle concept, metal leaf spring used for increased racket recoil (Newbery, 1955)

(b) Tool handle using springs to isolate user from tool vibration (Kubokawa, 1983)

(c) Spring mechanisms used to improve fit and security of handle sleeves (Adam, 1987)

(d) Vibration attenuation using mass attached to visco-elastic material (Takatsuka & Hariguchi, 1989)

(e) Section view of handle showing two separate sections and damping material to allow racket rotation (Walkhoff, 1989)

(f) Handle allowing rotation of head section about longitudinal axis (Henry, 1993)

(g) Handle constructed of blocks with rubber elements disposed between blocks to reduce vibration transmitted to the hand (Hsich, 1999)

(h) Damped handle section using visco-elastic material disposed between handle and head section of racket frame (Severa et al., 2002)

Figure 4.3: Images of some of the patent concepts
4.5 Development of sprung concept

Rapid manufacturing allows concepts to be generated and manufactured within a short time from conception. This speed of production is advantageous and has been used to develop prototypes for a sprung handle. The development of an initial prototype from sketch to CAD model to SLS prototype is shown in Figure 4.4. Simple helical springs were used in the first concept as they were easiest to visualise, and the first task of the concept development was to evaluate the sprung arrangements available for the handle concepts. By using spring-type elements between an outer handle shell and handle core it was possible to maintain a conventional handle outer shell. Therefore, the outer geometry of the handle: handle length, size and shape could be designed to conform to the configuration of a standard racket handle. This ensured that only the flex and vibration damping behaviour of the racket handle would be altered and that factors such as fit, shape and size remained constant.

Figure 4.4: Initial handle concept (from left to right) sketch of concept, CAD model, final SLS prototype

4.5.1 Selection of handle attachment method

As seen in Figure 4.4 the initial concepts were designed to slide onto an existing section of the handle shaft. However, to further the development of the concept, the method of attachment of the handle concept to the racket needed to be determined. The process selected also influences the geometry of the handle available to incorporate the sprung concept. Two conventional approaches to racket handle attachment exist. The first and most common current method used is PU foam moulding of the handle. Applying this method to a SLS produced handle would involve sintering the handle directly onto the racket frame or constructing the handle as a two part shell and attaching it onto the racket shaft using adhesive. Both these methods are impractical solutions. A more suitable approach is to use the pallet type arrangements as shown by David & Monty (2002) where the handle is injection moulded from a polymer. This handle pallet can then be slid onto the racket handle shaft and either glued or pinned in place. The pallet attachment method was used as it was much simpler to implement. With this system the handle concept slides over a section of the existing handle shaft. The constraints of using the pallet system on the handle design are observed at the racket end of the handle. For the rackets
used in this project, the handle shaft of the racket frame was approximately 26×19 mm in size. It was necessary for the handle concept to fit over this shaft with sufficient outer shell material to assume a firm fixing. The size of this handle was too large to permit sprung elements to be included into sections of the handle. The handle shaft was also required to be reduced in length to allow sprung elements to be incorporated. Between 20 and 30 mm of handle shaft was required to provide a secure attachment, leaving approximately 160 mm of the handle length available for the inclusion of sprung elements. The assembly of the final handle concept onto a racket frame using the pallet process is shown in Figure 4.5.

![Figure 4.5: Method of assembly of handle concept onto racket frame](image)

4.5.2 Selection of sprung arrangement

A decision matrix was used to evaluate all the potential spring concepts. Examples of the springs evaluated are shown in Figure 4.6. The criteria for the selection matrix were developed from the perceived needs of the player and the demands that this system would place on the spring system. Future developments of the handle concept may require a re-evaluation of these concepts. Typical criteria used in selection matrices such as material and production cost were considered irrelevant to this procedure as the manufacturing process was already determined as was the overall build envelope of the handle. The criteria used had equal weighting and the helical spring was chosen as the reference as it was the first sprung device used to embody the concept. The scoring matrix is shown in Table 4.1. For the concept design and selection it is useful to be able to determine the spring characteristics such as: spring stiffness and natural frequency. However, given that the spring material for these concepts
was Duraform PA, many of the required material properties for the spring calculations were not defined. One alternative was to use the material properties of nylon 12 for these calculations, however due to the anisotropic nature of Duraform it was believed that reliance upon calculations based upon a potentially different material would not be valid. Therefore the assessment of the spring's variability in stiffness was not made numerically but by comparing the range and suitability of options for altering the stiffness of each type of spring element and therefore comparing each spring on these factors.

![Compression Spring](image)
![Leaf Spring](image)
![Disc Spring](image)
![Bellow Spring](image)
![Cantilever Spring](image)
![Extension Spring](image)

Figure 4.6: Examples of the spring concepts evaluated

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Compression spring</th>
<th>Leaf spring</th>
<th>Disc spring</th>
<th>Bellow spring</th>
<th>Cantilever spring</th>
<th>Extension spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of modelling</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
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<td>Variability of stiffness</td>
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<td>-</td>
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<td>Device footprint</td>
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<td>-</td>
<td>0</td>
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<td>Torsional movement</td>
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<td>Failure detection</td>
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</table>

The compression spring, as used for the initial concept prototype, was rated the most suitable for application in the vibration reducing handle concept. By definition springs do not provide vibration damping but they are described as doing so in this thesis, this is due to the action of the spring movement being used to reduce the level of vibration transmitted into the section of the handle grasped by the player. This reduction is caused by the increased movement of the racket frame permitted by
the springs, the frame is therefore able to attenuate more energy and reduce the energy transmitted to the player.

The main advantages offered by the compression spring were good variability in stiffness achieved using simple variations in wire diameter, coil diameter, coil pitch angle and taper of coil diameter. More complex methods to influence the spring response such as variable wire diameters could also be implemented if required. The compression spring also allowed the simple constraint of the solid height of the spring when compressed, allowing the movement to be controlled. Other advantages afforded by the compression springs are that the nature of the structure allows some torsional movement of the spring, which is necessary to absorb torsional loads imposed by off-centre racket impacts. The final advantage of the compression spring is that it is a universally understood device and therefore is easy for the user to understand its function and purpose. The discarded concepts; leaf, disc, and cantilever springs were easier to model than the other spring concepts due to their simple geometry. However, they require a much larger footprint in the handle to work effectively and allow little or no torsional movement, providing the main reasons for rejection of these concepts. The bellow spring, essentially a stack of disc springs that behaves like an enclosed helical spring, gives problems with powder removal. The spring arrangement is also more difficult to model and vary. The final concept, the extension spring would be used to resist movement of the handle shaft in the opposite direction to all the other concepts. The problems identified with this concept are that because the spring is typically at its solid height when in the neutral position, powder removal is particularly difficult, with potential for fusing of the coils during sintering.

4.5.3 Selection of handle concept

The most intuitive way to develop the handle concept from the initial manufactured handle was to develop a series of variations iteratively, using a prototype and test method, with various product solutions developed and manufactured. This is a viable process with RM due to the speed with which concepts can be physically produced. The concept development stage also included player testing at each stage. Player feedback was then used to help with the product design direction. This testing also identified some weaknesses in the concept that would not be observed otherwise. Following various assessments, each design was then evaluated and changes were made before the next iteration produced. After several iterations (seven), a final prototype concept was selected and used for the basis of this research.

Figure 4.7 shows the development of the concept, with the various embodiments that were iteratively developed to yield the final selected concept (C3). From the initial concept two alternative approaches to the handle were explored. In the process of developing two separate strains, concept revisions were made to individual designs and if successful, were incorporated into both strains. The
Initial spring concept

Add CF shaft

Stiffen springs, add buttcap section

Make outer shell solid

Add CF shaft, refine outer shell shape

Fuse outer pixels so that solid shell for each row of springs

Change spring arrangement to allow better torsional movement

Combine concept C3 with split surfaces of B concepts to produce handle with 3 shell sections

Figure 4.7: Development of handle concepts from initial concept to final selected prototype
first strain of the concepts, 'B', was designed to have a conformal surface with individual handle shell sections or pixels on top of each spring. These surfaces allowed the damping to be more conformal to the gripping hand. The first major design change was initiated when the Duraform polymer was not stiff enough for unsupported use. Since the conventional racket handle was mounted on a composite (CF) shaft, a similar arrangement was incorporated. Due to the space requirements of the springs, a smaller diameter shaft of 10mm diameter was incorporated into the design. The nominal size of 10mm was selected as this was consistent with typical outer diameters of composite golf shafts, which were used for the shaft due to cost and availability considerations.

Additional feedback indicated that players found the positioning of the racket in the hand difficult without a tapered buttcap section. This feature was added to the design. The springs were also stiffened as players found the pixels moved considerably whilst they were gripping the handle. The next iteration (B3) abandoned the individual spring pixels in favour of separated handle shells that were connected to a row of springs. This allows the surface to move independently for each row of springs. The other strain of concepts, C, mounted a solid handle outer onto the spring elements so that the connection between the player's grip and the racket occurred via a series of springs aimed at isolating the impact vibrations. The first of these concepts (C1) was relatively crude and again the Duraform centre shaft was too flexible. These refinements resulted in C2, where the shape was altered to include a tapered buttcap area. The springs on the side of shaft not in the direction of impact were not suitable for the torsional movement generated by off-centre impacts. The following refinement produced C3. In this iteration, six springs were used per row, as opposed to the four orthogonal springs in previous embodiments. The six springs were orientated so that two were positioned in the direction of impact, with the remaining four springs positioned either side at an acute angle for off-centre impacts. This concept was found to perform well in pilot tests, with players finding the concept usable and not detrimental to their technique. This concept was therefore the selected prototype for further testing. The development of this concept from initial sketch to CAD model to produced handle is shown in Figure 4.8. With the C concept refined sufficiently, the 'B' and 'C' strains were combined, resulting in BC1. This concept possessed the layout of the C3 concept but the handle outer was split into three discrete sections so that the handle sections could move independently for each part of the gripping hand. Pilot testing showed that players found this handle to be 'strange' and detrimental to their technique as the handle surface didn't respond as the players would expect. It was therefore decided to abandon the separated handle shells until further investigation the the sprung mechanism was made.
4.5.4 Anatomy of selected concept

The key anatomy of the selected handle concept and terms used is shown in Figure 4.9, the handle is a one-piece construction with each key section coloured separately to allow distinction. The spring elements are blue, the handle shaft and mounting cavity are red and the outer shell is grey. The construction of the handle and methods of spring elements and composite shaft incorporation into the prototype are defined. The racket mounting shaft cavity is used to slip over a 25 mm long section of the racket frame’s existing handle shaft. The method of assembly has been shown in Figure 4.5. The handle cavity is designed to accommodate the remainder of handle shaft and provide an area for the novel handle to adhere to the racket frame. The length of 25 mm was selected to provide sufficient area for the handle to be bonded to the racket frame, while minimising the amount of the handle length occupied by the larger handle shaft so that a larger length of the handle concept could be devoted to the sprung arrangement. Figure 4.9 also illustrates the 13 rows of six springs per row, resulting in a total of 78 springs within the handle. The free length of the springs ranges between 6.35 mm for the vertical springs and 7.9 mm for the diagonal springs. The arrangement of the springs in the prototype allows a maximum achievable coil diameter of 8.5 mm (for a 2 mm wire diameter).
13 rows of compression springs

Handle outer shell

Compression springs (6 per row)

Buttcap section

Racket shaft mounting cavity

Handle outer shell

CF shaft hole

Racket mounting section

Powder removal holes

Pitch

Wire diameter

Free length (height)

Coil diameter

Figure 4.9: Anatomy of selected handle concept
An iterative approach was used to develop a final prototype concept. These iterations improved both the efficiency and consistency of the rackets assembled. The current process of assembly is shown in Figure 4.10. The following section describes each of the processes used to assemble a novel handled racket.
Assembly of prototype racket

This section details the processes in which a new Dunlop 200G racket is adapted to mount a novel construction handle (Figure 4.10).

C-1. The grip wrap is stripped from the handle of the new racket exposing the PU foam moulded handle. The handle in this state is shown in Figure 4.11.

C-2. The exposed handle section is cut 25 mm from the throat end of handle shaft, and PU foam removed to expose handle shaft. Exposed and cut shaft section are shown in Figure 4.12.

C-3. Central beam section of handle shaft is removed using a slot drill, creating a channel 10mm wide and 40mm deep to allow fixing of the new handle mount to the racket frame. This process clears the I-beam section that is found in the centre of the handle shaft. This section was originally created from joining both ends of the frame tubes to form the racket frame. The remnants of
A-I. To mount the novel handle concept a constant diameter composite shaft is used to replace the original section of the handle shaft. The shaft is selected to ensure that the racket maintains a playable stiffness as the stiffness of the SLS handle alone is significantly lower than that of a normal composite handle shaft. Due to the current geometry of the handle concept the shaft may have a maximum outer of 10mm. The required shaft length is 200 mm. The final length of this shaft is determined by the depth of the slot cut into the handle shaft (see process C-4) as only 180 mm of the shaft is accommodated directly in the handle concept.

B-I. To ensure that the shaft is mounted effectively into the racket handle shaft and to improve the shaft alignment, small nylon mounts were developed, shown in Figure 4.13. The mount edges are designed to locate against the inside of the racket shaft slot produced by the slot drill (Operation C-3).

B-2. The surface of the shaft was roughened using a fine grade sandpaper to promote adhesion with the epoxy resin. The shaft was then positioned in the nylon mount using the epoxy resin (shown in Figure 4.14) and allowed to cure prior to installation into the handle shaft.

C-4. The new shaft mount was placed into the slot in the racket handle (see Figure 4.15), ensuring that it is aligned to the racket principal axis. The mount is fixed into the racket throat using two-part epoxy resin.
C-5. The end of the handle is sealed using epoxy resin to prevent loose artifacts from creating annoyance (rattling) once the racket is assembled.

D-1. The SLS handle is built in the vertical orientation, to ensure the best finish for the bevelled edges for the outer shell and best production of the handle's angled springs. The build is completed on the SLS machine, taking between 6 and 13 hours for a single handle part, it remains encased in a powder cake. This powder cake is typically hot and is cooled for approximately 3 hours before parts can be removed. Once the cake is sufficiently cool the parts are broken free from the powder.

D-2. With the part removed from the cake, any unsintered powder is removed from the part. Unsintered powder that remains on the part can influence the effectiveness of the adhesive bonds between the handle and the racket. This powder can also become annoying and disruptive to players if it is not removed as it could become deposited from the handle during play.

C-6. Fine grade sandpaper is used to roughen the shaft surface to ensure improved adhesion with the new handle. Epoxy resin is applied to the shaft and inside of the handle cavity. The prototype handle is assembled by sliding the handle concept over the shaft and into position. Once the handle is located, the handle is positioned correctly with the flat faces of the handle aligned with the racket face. When the handle is set in position on the racket, epoxy resin is used to fill any gaps between the shaft, racket and handle.

C-7. With the adhesive cured, the racket moments, zero moment (weight), first moment (balance) and second moment (dynamic moment) are measured using Babolat RDC. The tolerances are $\pm 10$ grammes for frame weight, $\pm 2$ points for racket balance and $\pm 7$ points for the dynamic inertia. Rackets falling outside these tolerances will be modified using procedures in C-7.2 and C-7.3.
C-7.1. Rackets with measures that are out of tolerance by more than 12 grammes or balance point out by 5 points are adjusted by adding lead ingots if significant adjustment is required. If they are not more than several grammes outside the tolerance the adjustment can be done with lead tape. In general when assembling prototype handles, it is always necessary for weight to be added. Most standard handles have large lead ingots positioned under the PU foam to provide manufacturers with the required inertia characteristics. The adjustment of racket dynamic properties is required because of the manufacturing inconsistencies inherent in the processes used for frame production e.g. lay-up of pre-pregs, resin movement during moulding.

C-7.2. For significant alterations to the racket mass, lead ingots are used as utilising too much lead tape would produce a mis-shaped racket handle. Lead ingots are measured to the required quantity and shaped so that they can be passed into the centre shaft of the handle. Two-part epoxy resin is used to fix the lead securely into the shaft. The distance the lead is positioned down the shaft is dependent on how much the balance point needs adjusting. The closer the balance point to the required tolerance the further down the shaft the lead is deposited. Once the tolerances are satisfied, the lead insertion process is finished.

C-7.3. For rackets which require small adjustments, lead tape is used. This tape is adhered to the surface of the handle where necessary to influence the racket weight and balance appropriately. When adding lead tape to the surface of the handle, it must be ensured that whatever is applied to one side of the handle and equal weight of tape is applied to the opposite side, to avoid inconsistent dynamic inertia characteristics of the racket. Figure 4.16 shows the addition of lead tape to handle.

![Figure 4.16: adjusting racket properties with lead tape](image)

C-8. With the racket appropriately weighted and glued, the buttcap can be attached to the end of the handle to encase the springs and help protect them from damage in the event of the racket being dropped or items becoming lodged between them.
With the racket handle attached and completed, the handle can be wrapped using a standard grip wrap, producing a playable racket (Figure 4.17). The racket is configured to look and feel, identical to the original racket frame (Dunlop 200G), when swung only the impact perceptions may differ.

![Finished racket with prototype handle concept](image)

4.5.5 Cost analysis

Product cost is an influential factor when selling to the general population, as there generally exists a maximum price that a customer is willing to pay. Value analysis, as discussed previously by Campbell (2006), can be conducted to define this price. An estimated cost of the selected handle concept is provided using a cost model developed by Ruffo et al. (2006a).

![Handle build orientations used for cost analysis](image)

The material used for part production has previously been established as Duraform PA (3D systems). The recyclability of the Duraform powder is acknowledged in the model, a rate of 50% recyclable powder was used in this cost estimate and is below the manufacturer recommended limit of 67%.

Table 4.2 shows a cost analysis for the three build orientations shown in Figure 4.18. The cost for a full build (as many parts as can be fit onto a machine bed for one full build) and single part are shown. The vertical build orientation provides the lowest cost for a full build as it allows more parts in a single build. However, it is much more expensive for a single part due to the number of scanning layers required to produce the required part height. The increasing number of layers produces more waste unsintered material and therefore increases production costs as well as increased production time due to scanning of more layers. Figure 4.19 plots the individual part cost versus the number of
Table 4.2: Cost analysis of various build orientations for a handle part using Vanguard SLS machine

<table>
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<th></th>
<th>Vertical</th>
<th>Horizontal yx</th>
<th>Horizontal xy</th>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>No. Parts on bed</td>
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<td>60</td>
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<tr>
<td>Cost per part (£)</td>
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<td>Time to build (hrs)</td>
<td>62</td>
<td>56.6</td>
<td>51.83</td>
</tr>
</tbody>
</table>

|                      |          |                |               |
| **Single part:**     |          |                |               |
| Cost of part (£)     | 549.4    | 180.58         | 175.6         |
| Time to build (hours)| 13       | 5.9            | 5.7           |
| Material cost\(^1\) (£) | 275.97   | 59.12          | 59.12         |
| Time Cost\(^1\) (£)  | 274.43   | 121.46         | 116.48        |

\(^1\) Duraform Pa cost = £40/kg
\(^1\) Time cost = £20.5/hour

Vanguard bed dimensions, \(x=330\) mm, \(y=270\) mm, \(z=420\) mm

parts produced in a build. The chart demonstrates how part cost decreases rapidly with increasing number of parts in a build. Small peaks can be seen in the traces for each build orientation. These correspond to the placements of parts on a new build layer. The process of placing parts on a new build layer increases material usage and time costs noticeably for the first few parts on that layer until the cost is amortised by the placement of more parts.

Ruffo et al. (2006b) state that the model will over-estimate cost by approximately 12%, This is due to measures in the model that ensure that the time is not under predicted. Therefore it can be considered that further refinements of processes could improve costs. The current cost to a manufacturer of a top of the range racket frame is around £5 or less, therefore the cost of the handle is significantly higher than the cost of a current racket frame. However, the introduction of customised handles could pass the increased cost directly onto the consumer, justified as the necessary cost of customisation. This cost only reflects current market trends, as RM increases in prevalence, material costs will likely reduce. Work such as Ruffo et al. (2006a,b) also aids with identifying areas of unnecessary or large cost and over time these areas will be improved and more competitive production costs will become available.

4.6 Evaluation of handle prototype

A comprehensive analysis of the handle performance and issues is discussed at the end of the thesis. This section acknowledges the issues regarding the handle design and racket assembly. The first issues relate to the assembly of the handle onto a conventional racket frame. A conventional racket
has a handle shaft section, formed from the joining of the frame tubes, onto which the handle is mounted and moulded. An example of the handle shaft section is shown in Figure 4.20. This shaft provides the stiffness of the handle section. However, it needs to be modified to permit the inclusion of suitable sprung elements into the handle. To enable this, a small diameter composite shaft, bonded into the central section, replaces the original handle shaft (see section 4.5.4). The outer diameter of the composite shaft is 10mm, allowing sufficient space between the shaft and the walls of the handle shell for the placement of sprung arrangements. The main problem with this arrangement is that the mounting of the shaft is difficult since the internal wall finish of the racket frame is variable. It is therefore very difficult to mount a shaft into the existing handle throat section using the racket frame for reference. This could be improved with future handle development using racket frames specially developed for the assembly of novel handled rackets. Other improvements could be made by optimising the actual shaft used, as the current design uses a golf shaft of similar stiffness to the properties of the previous racket handle shaft.

A further area of handle manufacture requiring refinement is the process of adding weight into the handle to produce appropriate handle balance and inertia characteristics. If the racket is to be produced with the handle concept shaft already incorporated, it would be possible to customise weight the whole racket frame accordingly, knowing the weight and characteristics of the handle to
be attached. Other convenient methods such as injection of high density pastes or casting of suitably sized lead ingots would also be appropriate.

A significant issue with the current design was identified with initial testing and relates to the sealed nature of the handle concept. This means that it is difficult to determine whether any of the spring elements have failed in the handle. At present the only way to detect failure of the spring elements is either by cutting open the handle or when the failure of the elements causes catastrophic failure of the handle.

When examining potential future developments of the handle concept, the current embodiment makes no attempt to address possible customisation or optimisation of the stiffness of spring elements. This could be achieved using variation of the spring properties around each row of the elements or by varying the properties along the length of the handle. These methods could either improve vibration characteristics or improve the players perception of impacts. The following chapters will investigate the performance of the handle to determine the effectiveness of the concept.
Chapter 5

Human response to vibration

5.1 Introduction

With the handle concept determined additional research into the effects of vibration was required; this section provides an overview of the response of humans to vibration to understand the mechanisms relevant to the handle concept. The measurement of vibration is of significant interest to tennis research due to theories linking vibration from racket impact to injuries such as tennis elbow and related player discomfort. However, few of the previous studies have considered the human perception of vibration whilst performing a tennis stroke. An understanding of the characteristics of the sensory mechanisms involved in the perception of hand transmitted vibration is required to optimise the vibration to which people are exposed (Morioka, 2005). This section will discuss the human response to vibration and the consequences to the testing conducted. The effect of perception is a crucial factor to the handle design, as typically improvements to sports equipment are generally only of use if the player can perceive an improvement. Therefore, an understanding of the effects of vibration characteristics on perception is important for both study design and equipment design, to ensure appropriate measurements are taken and that equipment will perform in a manner that can be detected by the player. For example, a human is unable to detect high frequency sounds, so it is of little use to design an implement which modifies the high frequency sound produced upon impact, as no user would be able to detect this, unless the results are clearly detectable using another sense (i.e. the improvements are visible). To investigate this implement, it would be apparent that any perceived differences the user makes are not due to the ability to hear the improvement and therefore different measurements would need to be explored.

For vibration measurement at the hand, there are two acknowledged co-ordinate systems Figure 5.1 illustrates the anatomical and basicentric co-ordinate systems for the hand.

In this chapter results reported from studies are described using the basicentric co-ordinate system, with $X_{hb}$ referred to as measurement in the vertical direction, $Y_{hb}$ referred to as the lateral (axial) direction, and $Z_{hb}$ referred to as the horizontal direction.
Griffin (1997) and Carlsöö (1982) identifies the following physical variables that can influence the severity of hand-transmitted vibration.

- Magnitude of vibration
- Frequency of vibration
- Direction of vibration
- Duration of vibration
- Area of contact with vibration
- Contact force (grip force and push force)
- Finger, hand and arm posture
- Environment (e.g. temperature)

The frequency of vibration is key to determining the manner and extent to which vibration is transmitted through the hand-held apparatus and the extent to which it is transmitted through the fingers, hand and arm, and the body's responses to the vibration.

## 5.2 Vibration detection

Vibration experienced by the hand is detected by four classes of skin mechanoreceptors in the glabrous skin, they are classified according to their adaptation and receptive properties. The location of these receptors is shown in Figure 5.2. Slowly adapting fibres (SA) fibres include Merkel discs (SA 1), and
Ruffini endings (SA II) and fast adapting (FA) fibres include the Meissner corpuscles (FA I), which are more sensitive to frequencies above 5 Hz below approximately 40-50 Hz (Griffin 1990, 2005), and Pacinian corpuscles (FA II) that are responsible for the detection of frequencies above about 40 Hz. For the detection of vibration frequencies, four independent mechanoreceptive channels are identified, they are split into classifications of Pacinian (P) and non-Pacinian (NP) channels. The P channel provides sensations at high frequencies (greater than 40-50 Hz) using FA II fibres and summates over the stimulus duration and over the excitation area, processes known as ‘temporal summation’ and ‘spatial summation’ respectively (Verrillo, 1963). The NP channels have relatively flat frequency response to vibration displacement and do not exhibit spatial or temporal summation, but their sensitivity increases at frequencies below about 40 Hz. The response at lower frequencies is mediated by FA I fibres (Meissner’s corpuscles). In terms of the mechanoreceptive channels, the NP I and NP II channels are considered to be mediated by FA I and SA II fibres respectively (Gescheider et al., 2001), with the NP III channel mediated by SA I fibres (Bolanowski et al., 1986). Problems exist in identifying the roles of the various channels as testing is complex with the need to constrain the vibration to the area to be investigated to prevent vibration being experienced at other locations.

Figure 5.2: Cross-section of skin, (Griffin, 1990)

Each class of fibre is differently distributed over the skin surface of the hand and has distinctive responses to vibration stimuli (Johansson, 1978). The threshold curves of the the four types of nerve fibres have overlapping frequency ranges. The vibrotactile thresholds are thought to be determined by the nerve fibres that have the highest probability of detecting the applied stimulus.
5.3 Hand vibration induced disorders

Excessive exposure to hand-transmitted vibration can result in vascular and neurological disorders as well as individuals experiencing discomfort and interference with activities (Griffin, 1990). Vibration can also provide useful tactile feedback and assist in some tasks. Therefore an understanding of the characteristics of the sensory mechanisms involved in vibration sensing is required to optimise the vibration to which people are exposed (Morioka & Griffin, 2005). During the past century, it has been observed that repeated impacts (vibration and repeated shock) with sufficiently low magnitudes that they do not individually cause detectable injury, can also give rise to signs and symptoms of chronic disorders. Reynolds & Keith (1977) state that vibration frequencies between 100-200 Hz are primarily responsible for occupation hand-vibration diseases.

Tendonitis is a hypothesised cause emerging from the use of vibrating implements. In this condition the fibrous tissues of a tendon are torn and inflamed, often where the tendon joins the muscle to the bone, such as the outside of the elbow ('tennis elbow' or lateral epicondylitis)(Griffin, 1990). There is a wide range of studies that have investigated the role of vibration in tennis on arm injuries (Carroll, 1985; Kotze et al., 2003; Walther et al., 2002).

However only a few studies investigate subjective perceptions of impact vibrations (Davies, 2005; Stroede et al., 1999). However, none of the studies appear to acknowledge the fact that the mechanisms for perceiving vibration may be different to those that cause injury. Griffin (1990) suggests that detrimental effects on the hand and arm vary according to the direction of vibration and it is surprising that virtually all current vibration assessment procedures apply equal weighting to all three dimensions.

5.4 Thresholds of vibration perception

Several studies have investigated the threshold, equal sensation and annoyance contours of vibration experienced by the hand (Brisben et al., 1999; Miwa, 1967; Morioka & Griffin, 2005, 2006; Reynolds & Angevine, 1977) and numerous other studies have investigated similar characteristics of smaller areas of the hand such as perceptions of vibration in digits (Harazin et al., 2003; Lundstrom, 1984). The purpose of each of the threshold, equal sensation and annoyance tests are slightly different, and an explanation of the purpose of each of the tests is given below:

Threshold test: Threshold of perception tests are used to determine the relative sensitivity levels of the hand at various frequency levels. These tests typically involve the subject gripping a device which is excited at specified test frequencies. The amplitude of vibration is then increased or decreased until it is barely perceptible at each of the test frequencies, which is taken as the threshold value. Examples of these tests are found in Brisben et al. (1999); Morioka & Griffin (2005, 2006); Reynolds et al. (1977b).
Equal sensation: Equal sensation or equivalent comfort (as in Morioka & Griffin (2006)) contours determine the level of vibration at which different frequencies can be perceived to produce the same magnitude of sensation as a reference frequency of known magnitude. These tests involve a subject gripping an excitation device, which is vibrated at a known frequency and magnitude. The device is then excited at a test frequency and the subject is able to adjust the magnitude until they perceive the test frequency to be at the same level as the reference frequency. This process may require the subject to alternate between the test and reference frequency several times before making their decision. Examples of these tests are shown in Morioka & Griffin (2006); Reynolds et al. (1977b).

Annoyance test: Annoyance tests require a subject to grasp a controlled excitation device at a range of controlled test frequencies. At each test frequency, the level of vibration is increased until the subject determines that the sensation due to vibration is such that they no longer want to grasp the handle for an extended period of time. An example of this type of test can be seen in Reynolds et al. (1977b).

For investigation into subjective perception of tennis racket vibration, the threshold of perception curves are of most interest, as they examine the sensitivity of the hand for a range of frequencies. Figure 5.3 shows a comparison of the absolute threshold curves produced by Brisben et al. (1999); Morioka & Griffin (2005, 2006); Reynolds et al. (1977b). These studies are of most relevance as they investigated thresholds of subjects whilst gripping a cylinder (of varying diameters).

The threshold curves from the reported studies show two turning points in the thresholds at points between 20 - 50 Hz and 100 - 250 Hz, this indicates the transition from the NP I channel to the P channel and the frequencies between which maximum sensitivity are found, respectively. The observable inter-study differences are likely due to differing hand postures, grip forces used, push force, psychophysical procedures for measuring and subject population. Table 5.1 compares the fundamental elements of the studies. The studies comparing threshold perception for different vibration directions generally found that there was an increased sensitivity to vertical vibration relative to vibration in other axes at frequencies greater than 125 Hz (Morioka & Griffin, 2006; Reynolds et al., 1977b), with the hand being most sensitive to horizontal vibration at frequencies less than 50 Hz (Morioka & Griffin, 2006).

Reynolds et al. (1977b) demonstrated that humans tend to be more sensitive to broadband vibration than discrete vibration at frequencies below 100 Hz. The thresholds of perception for hand-transmitted vibration are heavily dependent on a number of factors. These factors include characteristics of the vibration such as frequency content, magnitude, duration and direction of vibration, subject contact force, contact area and contact point. Brisben et al. (1999) found that vibration thresholds were on average lower when the subject experienced vibration parallel to the skin surface
than when it vibrated perpendicular to the skin surface. Subjective influences include age, subject attention, temperature and previous exposure to hand-transmitted vibration. Subjects with acute exposure to vibration can experience temporary increase in vibrotactile thresholds due to a depression of the excitability of the skin mechanoreceptors. Reynolds et al. (1977b) also declared that subjects that possess a high threshold at one frequency will usually have a high threshold at other frequencies mediated by the same tactile channel.

The vibrotactile thresholds are also found to vary according to the location on the body. This is explained by the volume of receptors in particular locations. Morioka & Griffin (2005) investigated threshold perceptions of placing a palm of hand flat against a surface and gripping a cylinder. The threshold curves showed sufficient consistency between the two postures to hypothesise that sensitivity is not influenced by hand posture if contact area and gradients are unchanged. However, perception thresholds for the hand were found to be more than 10 dB lower than those for the fingertip, suggesting that spatial summation of the Pacinian channel enhances the detection of hand transmitted vibration.

To confirm whether thresholds were lower with larger contact areas due to a greater sensitivity at certain locations in the hand Morioka & Griffin (2005) investigated the effect of contact location at
The threshold perception curves are useful to determining the relative sensitivity levels of the hand at different frequency levels. However, equal sensation contours can also be examined to determine the level of vibration required for different frequencies to be perceived to excite the hand at the same level as a reference frequency of known magnitude. Reynolds et al. (1977b) used a reference frequency of 100 Hz to develop his equal sensation contours shown in Figure 5.4. Equivalent comfort contours are used to examine the rates of growth in vibration sensation with increasing vibration magnitude. It has been shown that this relationship is not linear and that in some cases a two-fold increase in vibration magnitude does not yield a two-fold increase in sensation. Morioka & Griffin (2006) investigated whether the rate of growth of sensation is dependent on frequency. His results are shown in Figure 5.5.

The results of Reynolds et al. (1977b) equal sensation suggest that an individual's relative perception of vibration is a function of the direction of vibration, the grip configuration, the amplitude of the reference signal and the frequency content of the signal. The results of Morioka & Griffin (2006) illustrate the vibration magnitudes required to produce the same strength of sensation across the frequency range. They also highlight which frequencies produce greater discomfort (lower acceleration at a particular frequency indicates greater discomfort at that frequency). With increasing sensation magnitudes the comfort contours approximate contours corresponding to constant velocity (acceleration increases in proportion to frequency). With decreasing sensation magnitudes, the contours become similar in nature to an absolute perception threshold. Sensitivity to vibration acceleration decreased with increasing frequency (from 8 - 400 Hz) at high acceleration magnitudes (greater than 2.0 ms$^{-2}$.

<table>
<thead>
<tr>
<th>Study</th>
<th>No. of subjects</th>
<th>Handle diameter (mm)</th>
<th>Grip Force (N)</th>
<th>Frequency range (Hz)</th>
<th>Vibration direction</th>
<th>Stimulus duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds et al. (1977b)</td>
<td>8</td>
<td>19</td>
<td>8.9 and 35.6</td>
<td>25-1000</td>
<td>Vertical, horizontal and lateral</td>
<td>N/A</td>
</tr>
<tr>
<td>Brisben et al. (1999)</td>
<td>19</td>
<td>32</td>
<td>subjective light to moderate</td>
<td>10 - 300</td>
<td>Lateral</td>
<td>1</td>
</tr>
<tr>
<td>Morioka &amp; Griffin (2005)</td>
<td>20</td>
<td>30</td>
<td>10</td>
<td>8 - 300</td>
<td>Vertical</td>
<td>3</td>
</tr>
<tr>
<td>Morioka &amp; Griffin (2006)</td>
<td>12</td>
<td>30</td>
<td>N/A</td>
<td>8 - 315</td>
<td>Vertical and lateral</td>
<td>2</td>
</tr>
</tbody>
</table>
rms) but sensitivity increased with increasing vibration frequency (from 20 - 100 Hz) at low acceleration magnitudes (less than 2.0 ms$^{-2}$ rms). For example, 10 ms$^{-2}$ rms hand transmitted vibration produced a greater strength of sensation at 20 Hz than at 100 Hz, whereas 1.0 ms$^{-2}$ rms, hand transmitted vibration produced a greater strength of sensation at 100 Hz than at 20 Hz. This magnitude dependence of the contours was more pronounced with vertical vibration.

5.4.1 Consequences for vibration measurement

The study of both perception threshold and equivalent comfort/equal sensation contours demonstrate that human sensitivity to hand transmitted vibration depends greatly on vibration frequency. The greatest sensitivity to acceleration for hand transmitted vibration is found in the range 80 - 160 Hz (Morioka & Griffin, 2006). It is therefore necessary to account for the frequency dependent changes in sensitivity (Morioka & Griffin, 2006). This is particularly important when reporting results that may be related to separate measures of human perception as un-weighted frequency spectra may not correctly display the frequencies responsible for the subjective perception. ISO 5349-1 provides a single frequency weighting, $W_h$, for the evaluation of human exposure to hand-transmitted vibration about any axis. This frequency weighting indicates a greatest sensitivity to acceleration at frequencies between 8 - 16 Hz, with acceleration reducing in proportion to frequency from 16 - 1000 Hz. Morioka & Griffin (2006) compares equivalent comfort contours to the ISO weighting function. They state that the magnitude-dependence of the the equivalent comfort contours demonstrate that a single linear frequency weighting cannot provide an accurate prediction of subjective judgements of discomfort.
caused by hand-transmitted vibration over a range of vibration frequencies and magnitudes from threshold to levels associated with discomfort and injury.
5.5 Vibration transmission to the hand and arm

A significant amount of research has been related to industrial tools and on a few tools there is significant vibration throughout the frequency range from a few hertz to tens of kilohertz. However, with the majority of tools, the acceleration spectra suggest that the dominant motion occurs in a much narrower range of frequencies, from approximately 8 Hz to about 1000 Hz. Reynolds et al. (1977b) found that in equal sensation tests subjects stated that the low frequency vibration induced to the hand (20-80 Hz) was felt in a region between the shoulder and wrist, while high frequency vibration (125-1000Hz) was primarily localised to the hand and fingers, therefore suggesting that the transmission of vibration was frequency dependent. At lower frequencies, the energy is not absorbed locally into the hand, high accelerations at low frequencies would inevitably produce large displacements rendering many tools unusable (Griffin, 1990).

The transmission of vibration is largely determined by the dynamic response of the hand, which depends on the physical characteristics of the individual, the contact area, grip force, push force, posture, etc. The influences of these factors can be quantified by measuring the energy absorbed in the hand instead of the vibration magnitude on the tool handle.

Several studies have measured the vibration at the wrist, elbow, and shoulder caused by vibration transmitted from the hand (Dong et al., 2004; Hennig et al., 1992; Reynolds & Angevine, 1977). Several of these studies remarked that for vibrations of frequencies around 10 Hz directed into the hand, subjects have been able to perceive vibration all the way up to the shoulder. However, as the vibration frequency was increased, the sensation of vibration tended to move down the arm until at frequencies above 100-150 Hz the sensation became primarily located in the fingers (Reynolds & Angevine, 1977). Dong et al. (2004) confirmed that vibration frequencies below 40 Hz could be effectively transmitted to the arms and shoulders, but frequencies above 100 Hz were mainly limited to the hand and less than 10% of vibration at frequencies above 250 Hz was transmitted beyond the wrist.

To investigate the mechanism of transmission for vibration directed into the hand and up the arm, Reynolds & Angevine (1977) attached eight piezo-resistive accelerometers to the locations shown in Figure 5.6 for eight subjects. Vibration was directed into the hand of the subjects using a 'T-bar' handle attached to an electromechanical shaker, on which an accelerometer was also attached. Grip forces of 9N and 35N were investigated as were palm and finger grip conditions.

Figure 5.7 shows the transmissibility results for each measurement location on the subject’s arm. The results are shown for the 9 N finger grip, the amplitudes of the 35 N palm grip are different, but exhibit the same general trends, and were not included in the published investigation. It can be seen that vibration becomes attenuated as it moves up the arm. The vibration was shown to be unattenuated through the finger to the measurement site at the back surface of the finger at frequencies
of around 100 Hz. Above 400 Hz, for vertical vibration, and 100 Hz for horizontal and lateral vibration, the vibration amplitudes of the backs of the fingers decreased as the vibration frequency increased. This implies that at frequencies below 100 Hz most of the vibration that was directed into the fingers was transmitted to the hand. As the vibration was progressively increased above 100 Hz, the vibration tended to become more and more localised to the fingers, and particularly to the area of the fingers directly in contact with the vibrating handle at frequencies above 100 Hz for horizontal and axial vibration and above 400 Hz for vertical vibration. Measures at the wrist in all three directions showed that the amplitudes at the wrist decreased considerably as frequency increased. Vibration amplitude at the wrist was around 10% the vibration amplitude measured at the fingers at 100 Hz and went down to 1% for vertical and 0.1% for the horizontal and axial directions for vibrations at frequencies of 1000 Hz respectively. The general amplitudes continue to decrease as the vibration progresses up the arm to the shoulder further highlighting the fact that vibration above 100 Hz becomes confined to the fingers. This is supported by Sorensson & Burstrom (1997) who investigated the transmission of
vibration energy to the human hand-arm system and found that for random vibration exposure (20-5000 Hz) about 50% of energy had been absorbed before reaching the knuckle, 85% before the wrist and about 90% before the elbow. Further analysis discovered that above 400 Hz almost all energy was absorbed below the knuckle of the hand, and was predominantly absorbed in the hand at frequencies above 60 Hz. Burstrom & Lundstrom (1994) discovered that a firmer hand grip produced higher arm absorption of energy per unit time, by a factor of 1.3 when grip force increased from 25 to 50 N and 1.1 when grip force increased from 50 to 75 N. The cause of the increased energy absorption is the viscous elements of the hand-arm system being influenced by muscle tension. A larger proportion of the hand-arm system is allowed to vibrate due to the higher muscle tension. Burstrom & Lundstrom (1994) also stated that the energy absorption in the human hand-arm system is dependent on the frequency, level of vibration, direction of vibration, the force of grip, and the flexion of the elbow.

Reynolds & Angevine (1977) examined the relationship between horizontal and vertical vibration between wrist and shoulder and found suggestions that longitudinal vibration (amplitudes normal to propagation of vibration) were transmitted along a bone almost unattenuated while transverse vibration (amplitudes perpendicular to propagation of vibration) are substantially attenuated as they travel along the bone. It was concluded that the attenuation of vibration up the arm occurs in the tissue adjacent to the bone and not in the bone.

There are some locations on the hand where a unity between vibration delivered to the hand and the measured vibration at the site can be found. Griffin (1990) found that the transmissibility between finger pad and nail can be near unity up to almost 1000 Hz for moderate or high contact forces.
5.6 Measurement of skin-mounted vibration

One of the principle issues regarding vibration measurements is the location of the measurement site and the consistency of the measurements taken. The sites of common vibration measurement for tennis research include the hand, wrist, elbow and shoulder. Lafortune et al. (1995) states that direct attachment of an accelerometer to bone constitutes the most accurate means of measuring the shock travelling through the skeletal structures of the body. Bone mounted transducers (BMT) are typically employed using pins inserted through the skin directly into bone at the site of interest so the vibration can transmit directly through the pin into the transducer, these are known as Kirschner wires and shown in Figure 5.8. Although this method is the most accurate and has been used at various locations in multiple studies, it requires medical skill and restricts the number of measuring sites and number of willing participants.

An alternative to using BMTs is to use surface mounted transducers (SMT) to estimate the bone vibration. The concerns with using SMTs is that skin does not behave in a linear fashion as would an isotropic material (Payne, 1991). Figure 5.9 displays a stress-strain curve for normal human skin, and indicates that the properties are influenced by repeated applications of force and is therefore a unique material to take measurements from. The non-linear behaviour is attributed to the unravelling of wavy collagen bundles of the skin. As the force increases, more fibres are subjected to a direct stretching force, causing the non-linear shape of the force-displacement curve. It has also been suggested that the frequency and damping of vibrations experienced by the human body are controlled by muscle activity within the body's tissue (Burstrom & Lundstrom, 1994). Griffin & Kitazaki (1995); Mansfield (1998) have both used skin mounting of accelerometers followed by a correction method to convert the result of the skin measurement into a representative measurement of the bone acceleration. The following section will summarise the methods, results and conclusions raised by these publications.
Figure 5.9: Stress-strain relationship for normal human skin (a) initial application of stress. (b) Second application. (c) Third application. Note: Further cycles will lead to a 'pre-conditioned state' giving rise to consistent data (Payne, 1991)

5.6.1 Data correction of surface measurements of vibration

A study examining buttocks tissue (Kitazaki, 1994) showed that non-linear effects were found to influence the correlation of bone vibration with vibration measured at the skin. The loosening effect of the skin has been likened to the thixotropic property of some gels which liquefy when shaken and solidify when left unmoved, and could help to account for the lower stiffness and consequent lower resonance frequencies with higher vibration magnitudes. Pope et al. (1986) compared the displacement responses of the vertebra L3 from surface measurement and direct measurement and found a significant difference. There have been several methods to minimise or correct for the effect of the local tissue-accelerometer vibration on surface measurements. One method is to apply a preload to the surface mounted accelerometers, this increases the stiffness of the local tissue and minimises the effects of local tissue-accelerometer vibration. Methods include mass preloading, spring preloading and strap preloading (Lafortune et al., 1995; Valiant et al., 1987; Wakeling & Nigg, 2001; Ziegert, 1979). Valiant et al. (1987) suggested that skin-mounted transducers may exhibit a loss of the high-frequency components due to the movement of the soft tissue between the accelerometer and the bone. They believed that these movement artefacts could be minimised using a low-mass accelerometer and pre-loading it onto the skin surface. However, it has been contended that the application of a preload can create additional resonant systems. Work by Davies (2005) to investigate the effect of preloading
accelerometers on the knuckle for vibration measurements using tape found that there was no noticeable difference in the accelerometer measures between the preloaded and non-preloaded accelerometer measurements and that the application of preloading at the knuckle was awkward.

Hinz et al. (1988) and Smeathers (1989) proposed a free vibration test with the accelerometer attached on the body surface to estimate the natural frequency and damping ratio of the local system. The correction frequency function was calculated using the estimated natural frequency and damping of the accelerometer attachment at the spine. The estimated damping ratios ranged from 0.1 - 0.5, but no validation of the method was shown. Griffin & Kitazaki (1995) and Mansfield (1998) proposed improvements using a similar method to correct for the measurement at the surface of skin. Both used a single degree-of-freedom linear model to represent the local tissue accelerometer system at the spine. Assuming that local motion of the skin is linear with respect to the motion of the body, the transmissibility of the local tissue-accelerometer system can be estimated from the shock response of the accelerometer, and then used to find the damping and natural frequency of the mounting. Mansfield (1998) displaced skin-mounted accelerometers by 10mm to generate a transient response. He then followed the method of Griffin & Kitazaki (1995) to equalise the local response of the accelerometer on the skin surface. The Griffin & Kitazaki (1995) system can be described by the mass of the accelerometer and tissue involved in local vibration, \(m\), the spring rate of the tissue, \(k\) and the damping coefficient of tissue, \(c\), attached to the body system, which may have multi-degrees-of-freedom, Figure 5.10 shows a representation of this system.

\[
m\ddot{x}_m(t) + c (\ddot{x}_m(t) - \ddot{x}_l(t)) + k (x_m(t) - x_l(t)) = 0
\]  

(5.1)

Figure 5.10: Model for the local system of an accelerometer mounted on the body surface (from Griffin & Kitazaki (1995))

The input point in Griffin & Kitazaki (1995) was the buttocks of the subject. The true acceleration of the spine is \(\ddot{x}_l(t)\). The measured acceleration is \(\ddot{x}_m(t)\) which is the response to the input of \(\ddot{x}_l(t)\) at the local system of \(\ddot{x}_l(t)\). The equation of motion about the mass of the local system is shown in Equation 5.1.
By solving Equation 5.1, the correction frequency function to eliminate the effect of local tissue-accelerometer vibration from the surface measurement is defined by the inverse transfer function of the local system, and is given by Equation 5.2

$$C(\beta) = \frac{1 - \beta^2 + 2i\zeta \beta}{1 + 2i\zeta \beta}$$

(5.2)

where $C(\beta)$ is the correction frequency function, $i^2 = -1$, $\zeta$ is the damping ratio, $\beta$ is the frequency ratio. These equations are further modified to show that the modulus of the free vibration response reaches a peak at the natural frequency. The damping of the system can be estimated from the width of the modulus curve around the natural frequency peak. With $\Delta f_-$ and $\Delta f_+$ in the lower and upper sides corresponding to the half power points of the peak, the damping ratio in Equation 5.3 is obtained, where $f_o$ is the natural frequency of the system.

$$\zeta = \frac{1 - (1 \pm \Delta f_/f_o)^2}{2(1 \pm \Delta f_/f_o)}$$

(5.3)

When damping is small, Equation 5.3 can be approximated to $\zeta = \Delta f_/f_o$. This approximation is not appropriate for the heavy damping of the human body though. A correction function is obtained by substituting the natural frequency and damping ratio into Equation 5.2. Griffin & Kitazaki (1995) used four different masses of 6.3, 15.8, 25.4 and 34.5 g at each measurement site. These masses were produced by attaching additional necessary mass to an initial accelerometer, card and adhesive tape mounting of mass 6.3 g. Local free vibration was introduced at the measurement sites using a thread connected to the thin stiff card at the base of the accelerometer. This thread was pulled up or down and then cut to cause local free vibrations. The excitation process was repeated four times at each site for each accelerometer mass. The correction frequency functions were then calculated using the estimated natural frequencies and damping ratios. For the dynamic test, Griffin & Kitazaki (1995) sat subjects on a rigid seat attached to a vibrating mechanism. The subjects were kept in the same position as in the free vibration test. The subjects were then exposed to a vertical random vibration of magnitude $2.0 \text{ m/s}^2 \text{ r.m.s.}$ in the frequency range of 0.5 - 35 Hz for a duration of 1 minute. Four experiments were conducted, one for each accelerometer mass, showing good repeatability with each experiment run at the various measurements locations. The results for the responses of the four different accelerometer masses showed a systematic trend as the increased accelerometer mass caused a decrease in the natural frequency. Large differences were found in the estimated natural frequencies and damping ratios between the subjects and measurement sites used in the testing. Griffin & Kitazaki (1995) also noticed a systematic trend in the transfer functions from the seat to the vertebra. Increasing accelerometer masses were observed to increase the transmissibilities and phase lags throughout the
observed frequency range. By applying a correction function, the differences in transmissibilities and phase lags were dramatically reduced producing almost identical results. Mansfield (1998) measured the transient response of the system, taking a Fourier transform of the 1 second measurement period containing the response. The modulus of the Fourier transform gave the resonance frequency ($f_o$) from the peak in the response. Damping was found from measuring the width of the peak in the modulus of the Fourier transform by determining half power points. The two frequencies ($f_{\pm}$), on either side of the peak. Where the magnitude of the modulus of the Fourier transform is equal to $1/\sqrt{2}$ of the magnitude of the peak where found. If $\Delta f_{\pm}$ is the mean difference between the resonance frequency and the half power points, the damping ratio for a heavily damped system is as shown in Equation 5.3.

The correction response function is given in Equation 5.2, where $\beta$ is the ratio of the frequency to the resonance frequency. The measured transfer functions between the seat and body for Mansfield (1998) were divided by the correction function to obtain a corrected transfer function, minimising the effect of local tissue-accelerometer dynamics. Figure 5.11 shows the effect of correction on the original transmissibility.

Figure 5.11: Effect of data correction on seat to L3 z transmissibilities for subject 1 measured at 1.0 ms$^{-2}$ r.m.s. (Mansfield (1998))

5.6.2 Issues with data correction of SMT vibration measures

The compensation of SMT vibration is well developed for applications such as the measurement of whole-body vibration for the studies of vehicle vibration and related studies. However, there are several issues which need to be considered for the application of these techniques to hand measurements for tennis. It has been found that increasing the contact area of the accelerometer site will increase the stiffness of the tissue and stabilise the motion of the accelerometer (Griffin & Kitazaki, 1995). In some cases this may be desirable, but for hand measures where the size of the accelerometer and attachment are kept as small as possible for both weight and logistics reasons, it isn't always favourable. With knuckle measures, a degree of stiffness is required at the site to help stabilise the accelerometer, but too large an accelerometer attachment is uncomfortable for the subject due to the way the skin moves
around the knuckle. The investigation into the effects of accelerometer mass on the skin surface on vibration measured by measuring the response of accelerometer arrangements of increasing mass is also awkward for hand measures. To achieve a range of masses similar to Griffin & Kitazaki (1995) would require a significant addition of mass to the accelerometer arrangements conventionally used for hand measurements with tennis. Therefore the accelerometer arrangements would require larger contact areas, which is known to adjust the stiffness of the skin, or the accelerometer arrangement would have to be greater in height which can be impractical. Griffin & Kitazaki (1995) showed that the correction procedure was limited to frequencies below the estimated natural frequencies of the local system. They also concluded that variability in the natural frequencies and damping ratios between the subjects prevented the determination of a standard correction frequency function. This conclusion suggests that not only can generalisations not be made about the level of compensation required, that each subject tested would require compensation testing for each proposed measurement site. The method proposed by Griffin & Kitazaki (1995) is limited to frequencies below the natural frequencies of the local system, which for the spine was <50 Hz. This level of vibration may be suitable for spine vibration corrections but for tennis vibration measurements the main frequency range of interest is between 100-200 Hz and therefore this correction would not identify the effects in this region. This conclusion is supported by Kim et al. (1993) who found that the use of lightweight accelerometers can expand the working range for correction of skin mounted acceleration, but that it was impractical for frequencies higher than 100 Hz. Payne (1991) suggests that skin tests that rely on a good adhesion of contact between the skin and test device, should use cyanoacrylate cement or medical superglues to bond the device to the skin. These products do not suffer from effects such as creep and double sided tape has been shown to exhibit some slippage effects, which could cause discrepancies in the results. He also suggest that knowledge of the skins structure i.e. depth of epidermis was important for identifying factors in skin mechanical performance and inter-subject variability. For tennis research it is favourable to use double-sided tape or similar due to the need to quickly change or move the attachment. In addition, locations such as the knuckle show varying levels of tension in the skin depending on the grip used by the player, the use of glues on the skin surface can be restrictive to this movement. The displacement of an accelerometer to generate a transient response as conducted by Griffin & Kitazaki (1995) has been found to be particularly problematic at the knuckle. The tension and stiffness of the skin at the knuckle varies between subjects and when investigated with the hand in a gripping posture very high skin tension can be found, which makes the displacement of the accelerometer extremely awkward to generate a transient response.
5.7 Discussion

Much of the research on human sensitivity to vibration has been conducted for the assessment of equipment such as power tools or the determination of vehicle comfort. Therefore much of the work is concerned with continuous vibration exposure and the generation and detection of vibration-related maladies e.g. Reynaud's disease. Sports impacts are typically short duration and cases of serious vibration disease from these type of vibrations have not been reported. However, to date there are no studies documenting the effect of short duration vibration on human sensitivity and therefore it can be speculated that it is possible for the perception of short duration vibration to be slightly different to that of continuous vibration. A summary of the main points from the human sensitivity to vibration research.

- The perception of vibration is conducted by four different classes of skin mechanoreceptors. Each type of mechanoreceptor is responsible for a different frequency range. Each mechanoreceptor is differently distributed about the skin's surface resulting in parts of the body providing differing sensitivities to certain frequencies.

- The perception of vibration and injury caused by vibration can be two separate issues, as it is possible for vibration frequencies of low sensitivity to cause injury.

- The effect of exposure to high levels of vibration or vibration trauma is that overall vibration sensitivity can be reduced in the exposed areas.

- Humans are most sensitive to hand-transmitted vibration in the frequency range 100-250 Hz.

- A two-fold increase in vibration magnitude does not yield a two-fold increase in strength of sensation. A smaller increase is more common with the degree of increase in sensation being frequency dependent.

- Individuals who are more sensitive to a certain frequency will be sensitive to all frequencies mediated by the same tactile channel.

- The greater the transmission of vibration from the source the more nerve fibres are activated, which results in increased sensitivity.

- For vibration delivered to the hand, frequencies above 100 Hz are generally confined to the hand and frequencies above 400 Hz are generally confined to the fingers.

It was decided that the determination of a compensation factor for subject based measurement was not feasible for this project. The nature of the testing to be conducted requires a large number of subjects with different hand postures for each stroke. Consequently, the determination of the
compensation factor for each subject with a hand posture corresponding to each racket grip is too demanding, especially given the difficulties of conducting procedures (i.e. the local free vibration) on sites such as the knuckle are particularly awkward. Discussion with relevant academics suggested that the use of as small mass transducer as possible (< 2 grammes) is one approach to minimise the effects of independent skin motion. Otherwise alternative approaches include the measurement of the vibration in close proximity to the point of contact between the vibrating device and subject. The effect of the accelerometer mass can be acknowledged as a source of inaccuracy in the measurements made, but the effects are not expected to influence the determination of any significant differences between subject measures. Subjects will also use more than one racket each and therefore the measurement inaccuracies between rackets should be relatively consistent.
Chapter 6

Analysis of novel handle concept: Test methodology

6.1 Introduction

Following the construction and initial testing of a novel racket handle concept, the performance of the handle concept was examined under conventional usage. Studies have measured the vibration from various tennis impacts at the hand (Fairley, 1985; Maeda & Okauchi, 2002), wrist (Hennig et al., 1992; Li et al., 2004; Naß & Hennig, 1998; Tomosue et al., 1994; Walther et al., 2002), and the elbow (Hennig et al., 1992; Iwatsubo et al., 2000; Li et al., 2004; Walther et al., 2002) as well as the racket itself (Fairley, 1985; Iwatsubo et al., 2000; Stroede et al., 1999; Tomosue et al., 1994; Walther et al., 2002). Researchers investigate player vibration to: develop understanding of the role of vibration on the condition of 'tennis elbow' (Carroll, 1985; Kotze et al., 2003; Walther et al., 2002), to determine the effectiveness of vibration reducing technologies (Iwatsubo et al., 2000; Kotze et al., 2003; Li et al., 2004; Stroede et al., 1999; Tomosue et al., 1994), or to investigate the physiological or technique effects on the transmission of racket vibration to the player (Fairley, 1985; Hennig et al., 1992; Maeda & Okauchi, 2002; Naß & Hennig, 1998). Measures of vibration have also been conducted in other sports on both the implements and the interface between player and implement to investigate both performance and perception effects. In golf, Roberts et al. (2001) and Hocknell et al. (1996) investigated the influence of vibration from impact between a golf ball and driver on player perception of the equipment. Noble & Walker (1994) investigated the links between measured baseball bat vibration characteristics and perceived ratings of vibration. The purpose of this testing is to investigate the performance of the novel racket handle concept. Two main aspects of performance are examined: the measured performance of the handle concept versus a standard racket handle and player perceptions of the novel racket handle. The combination of these distinct areas enables influencing factors of a player's perception elicited by racket handle design to be further investigated.
6.2 Measurement of subjective data

There has been a significant amount of research investigating the impact between a ball and tennis racket whilst gripped by a human. Studies have investigated a wide range of issues including the role of the grip pressure on racket and limb vibration, and the effect of different racket characteristics on the received vibration. The aim of to these investigations has been to investigate the causes of discomfort or injury from a tennis racket and how they can be influenced by both the equipment used and the player's technique. However, there are few studies that investigate the subjective perception of the impact characteristics. Studies that have done so have evaluated subjective responses during unconventional tennis tasks. Examples of these include balls being fired at rackets held stationary by players (Hennig et al., 1992; Li et al., 2004; Stroede et al., 1999) or ball dropped onto rackets held by a player (Maeda & Okauchi, 2002). From these studies only Stroede et al. (1999) conducted subjective testing to analyse perceived discomfort from varying impact conditions. This was conducted using a visual analogue scale (length 5 inches) where the subject was asked to place a vertical mark on a scale with 'comfortable on impact' and 'uncomfortable on impact' at the scale extremes. Iwatsubo et al. (2000) also used subjective scales to investigate the perceived vibration and sweet spot of tennis rackets equipped with a prototype impact shock protection system. A 1–5 scale was used to investigate the impact shock transmitted to arm, the paucity of vibration and the size of the racket sweet spot. A five-point scale was also used to study pain in various hand location of players using two types of aluminium softball bat (Noble & Walker, 1994). The players rated the amount of pain in each location, with 0 corresponding to no pain, 1 slight, 3 moderate, and 5 severe pain or discomfort. Noble & Walker (1994) used this data to analyse subjective preferences for bat impact locations and the effects of bat inertial characteristics. While not directly comparing subjective perceptions to individual objective measures, Hocknell et al. (1996) compared results of a subjective investigation into perceived sensation in the hands for a combination of two golf clubs and three golf balls. Analysis of frequency spectra of the club-ball vibration combinations suggested that for golf, the sensation in the hands is dominated by club vibration in the range 0–2.5kHz. Roberts et al. (2001) also investigated subjective perceptions and vibration measures. However he directly compared individual's perceptions to their objective measures to determine the influence of a variety of club constructions. Further analysis of the techniques used by Roberts et al. (2001) are included in Section 6.2.1.

The use of psychometric tools to measure subjective opinions of sports equipment has been used in golf by Barrass et al. (2006); Roberts et al. (2005) and with tennis balls by Davies (2005); Steele (2006). There is a large breadth of methods available to investigate player's subjective perceptions. The two most commonly used methods in sports equipment testing are the use of paired comparisons (Barrass et al., 2006; Davies, 2005; Roberts et al., 2005; Steele, 2006) or the use of scaled response
questionnaires (Roberts et al., 2001; Stroede et al., 1999). The use of paired comparisons is advantageous for comparing items where subtle differences exist. The side-by-side comparison facilitates the identification of differences by the subject. The drawback of paired comparisons is the number of individual comparisons required from each subject to form a complete test. The relationship between number of variables and required number of comparisons is shown in Table 6.1.

Table 6.1: Number of comparisons per items investigated

<table>
<thead>
<tr>
<th>Number of items</th>
<th>Number of comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
</tbody>
</table>

When the task or equipment evaluated is short or simple in nature such as evaluating colour intensities a high number of comparisons may be acceptable. However, more complex or longer duration tasks are susceptible to issues such as participant boredom and fatigue. The paired comparisons technique was deemed unsuitable for this study due to the number of comparisons required for racket testing. The alternative of scaled response questions have been previously used in Chapter 3 to identify grip/handle characteristics in the structured relationship model.

Roberts (2002) investigated the methods of implementing scaled response questions for measuring subjective responses of golfers using drivers. One method requires subjects to rate the driver versus a reference level provided by either a control racket or relative to each individual’s ideal feel. An example of this type of question is shown in Figure 6.1. Limitations of this technique are that when using a control racket, test subjects will need to frequently re-use the racket to refresh their perception of it’s performance and can receive varying evaluations of the racket with each use.

![Figure 6.1: Example of scaled response question using ideal feel or reference racket](image)

Rating versus ideal feel level can be found to use only one half of the scale as it is unlikely for qualities such as control or comfort that a test racket can be anything but less than ideal feel.

Although problems relating to a common reference level for subjects were identified, in subsequent work by Roberts (2002) techniques were developed to overcome these limitations. The study indicated that although players did not initially posses a reference level, they begun to develop their own after
a number of shots. Statistical techniques were implemented to overcome the variations between each player’s reference level and the subsequent variations in their use of the scales were investigated. These processes are discussed in more detail in Chapter 7.2.

6.2.1 Selection of scaled response questions

The scaled response questions used in the testing were selected from examination of the structured relationship model using previous experience of questions or sensations that players were able to attend to. A series of preliminary tests were conducted to ensure questions were understood and relevant. It was important that the selected questions corresponded to racket properties which could be influenced by the handle construction. The characteristics selected for investigation were:

- Level of vibration in hands
- Amount of racket control
- Racket power
- Racket flexibility
- Discomfort during stroke

The vibrations from impact were frequently discussed by players during the structured relationship model interviews and pilot testing. Since the handle concept is aimed at reducing the vibration from impact, it was essential to include a subjective measure of vibration from the shot. Racket characteristics of power and control were consistently discussed by players during feel map interviews. Informal pilot tests again highlighted the importance of these characteristics as they were frequently mentioned by players when discussing a racket’s performance. Although racket flexibility was not a characteristic that emerged from the feel map, it was included to allow players to express possible effects of the novel handle concept on the racket. To avoid misleading questions, the term flexibility was removed from the question and replaced with racket feel, with the term flexible used for orientation at one end of the scale. The discomfort during stroke characteristic was included to allow players to acknowledge whether the racket arrangement was comfortable for them and to locate any regions of discomfort for particular rackets or strokes generated. This question is similar in nature to those posed by Stroede et al. (1999).

It has been found difficult to provide ratings for several differing feelings after each shot, therefore only the level of vibration experienced was posed after each shot, it was desirable to limit the number of feel characteristics investigated at one time. The amount of racket control, racket power, racket flexibility, and discomfort experienced during the stroke were only rated upon the subject’s completion of testing with each racket. Concerns exist over eliciting scaled response data to multiple questions
from subjects at the same time. Players either possess or build preconceptions of the relationships between the different characteristics they are being asked to rate. These preconceptions can influence the actual sensations and result in erroneous results and correlations between characteristics, which may not occur if the characteristics were investigated independently. Due to the time restrictions to conduct the test and the specialised population required to participate it was not possible to conduct separate tests for each scaled response characteristic that was to be investigated. Therefore, the use of several scaled response questions at once was unavoidable, with acknowledgements made to possible correlations that may occur. The scaled response questions used are shown in Figure 6.2. Scale orientation is provided using vocabulary from the structured relationship model, where possible, at either end of the scale. All scales were orientated consistently so that high value or desirable qualities were found at the 9 end of the scale, and less desirable or lower value qualities at the 1 end of the scale.

The discomfort question is configured slightly different to the other questions. Subjects describe the areas of their gripping arm affected by the discomfort and the magnitude of discomfort in each respective area. The discomfort question is shown in Figure 6.3. The key areas of arm discomfort for tennis have been identified in studies such as Priest et al. (1980b); Stroede et al. (1999).

Copies of the questionnaire sheets as presented to the subjects are shown in Appendix C. A large scale version of all of the questions was placed in view of the subject’s testing to serve as a reminder of the questions to be completed. The player’s subjective responses were marked on individual sheets for each shot type performed. This data was recorded to allow concurrent analysis of the subjective data with recorded objective data of the racket.
<table>
<thead>
<tr>
<th>How much vibration did you feel in your hands?</th>
</tr>
</thead>
<tbody>
<tr>
<td>No vibration</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How much control did you feel you had for the shot?</th>
</tr>
</thead>
<tbody>
<tr>
<td>No control</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How powerful did the shot feel?</th>
</tr>
</thead>
<tbody>
<tr>
<td>No power at all</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How did the racket feel?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racket flexible</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Figure 6.2: Scaled response questions used

<table>
<thead>
<tr>
<th>Did you experience any discomfort using the racket?</th>
</tr>
</thead>
<tbody>
<tr>
<td>No discomfort</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>Hand</td>
</tr>
</tbody>
</table>

Figure 6.3: Discomfort scaled response question
6.3 Measurement of objective data

The measures used to quantify and assess the physical performance of various racket constructions and differing subjects will be discussed in the following section. Objective measures are examined concurrently with the subjective data to determine the physical racket properties influencing subjective perceptions. The aim of this study is to ensure objective measures are investigated using tennis strokes performed in situations as close to in-game tennis play as possible, and to provide information for the refinement of future racket designs.

6.3.1 Measurement of racket vibrations

Numerous studies have investigated the vibration experienced by tennis players when performing specific strokes. These studies examined various aspects of the vibration experienced at impact including the effects of vibration on tennis elbow (Fairley, 1985), the effectiveness of racket damping technologies (Iwatsubo et al., 2000; Li et al., 2004; Stroede et al., 1999; Tomosue et al., 1994; Walther et al., 2002), and the transmission of racket vibration to the hand and arm (Fairley, 1985; Hennig et al., 1992; Maeda & Okauchi, 2002). They have also used a variety of measurement locations, including measures from the racket only (Brody, 1989), measures from the limb of the subject performing the stroke (Hennig et al., 1992; Li et al., 2004; Maeda & Okauchi, 2002; Stroede et al., 1999), and measures of both the racket and the subject (Carroll, 1985; Fairley, 1985; Iwatsubo et al., 2000; Kawazoe, 2000; Naß & Hennig, 1998; Tomosue et al., 1994).

A study by Plagenhoef (1970) investigating the effect of vibration transmission to the arm from rackets of varying characteristics discovered that the impact location, rather than the racket type, produced the biggest influence on the forces transmitted to the arm. Elliott et al. (1980) also investigated impact location of a constrained hand-held racket in the forehand orientation. He discovered that vibration amplitudes increased with longitudinal and transverse deviation from the centre of the string bed. However, the rate of this increase was found to be dependent on the racket properties. Both Hennig et al. (1992); Naß & Hennig (1998) concurred finding increases in vibration from longitudinal deviations of impact. Hennig et al. (1992) documented that the off-centre impact locations resulted in three times higher peak-to-peak accelerations.

Studies have also investigated the effects of vibration damping devices such as string-mounted dampers on the measured vibration transmitted to the forearm. Li et al. (2004); Stroede et al. (1999) found that string dampers do not reduce the vibration transmitted to the hand. Both these studies constrained the movement of the racket and subject to static grasping of the handle to achieve repeatable impact conditions. The racket impact vibrations of greatest discomfort are caused by the first vibration mode from 80–200 Hz (Brody, 1981, 1987; Hennig et al., 1992) depending on the stiffness of the racket frame tested. These values appear to agree with independent assertions that the greatest
sensitivity to acceleration for hand transmitted vibration is found in the range 80–160 Hz (Morioka & Griffin, 2006). Since racket strings typically have much higher natural frequencies (600–1000 Hz) the reduction of frequencies by string dampers do not produce an effect on the frequency range of interest.

The effects of player technique have been shown to influence transmitted vibration. Hennig et al. (1992) discovered significant differences between subjects for the acceleration integrals from impacts. Brody (1989) discovered that both the grip force and location of the applied grip produced a noticeable effect on the vibration experienced by the player. Hatze (1976) also demonstrated that a very tight grip increases the power of the stroke, and the magnitude of vibrations transmitted to the hands, whereas a loose grip reduces the shocks at the hand at the expense of the racket power.

Many other studies have investigated vibration transmitted to the hand from tennis rackets. These are discussed in further detail in the relevant parts of this section.

6.3.2 Test rackets

Work by Hennig et al. (1992) suggests that subject-specific differences would be observed for the vibration data from racket impacts. As a result, several variations of the handle concept were produced for testing so that the effect of the subjective differences and preferences could be determined. Similar to the structured relationship model, Dunlop 200G racket frames were used for testing. Four versions of the novel handle concept and one standard racket handle were chosen and attached to racket frames.

Handle concept configuration

The handle concepts are designed such that the stiffness of the spring elements located between the handle shell and central shaft can be variable, to allow for future personalised customisation. Due to a lack of material information regarding the Poisson ratio of Duraform PA and the anisotropic nature of the material in sintered form, no investigation was conducted on the varying effects of build parameters on the modulus of elasticity of Duraform PA. Thus player testing was required to allow subsequent optimisation of the handle concept. A simple approximation of spring stiffness was used to produce handles with various spring elements, with future work planned to comprehensively analyse the material properties of Duraform PA in relation to the formation of springs.

Spring index \( C \) was utilised to determine a series of spring elements for the racket handles (Equation 6.1),

\[
C = \frac{D}{d}
\]  

(6.1)

where \( D \) is coil diameter and \( d \) wire diameter of the spring. Using the current design geometries of the handle concept (i.e. keeping shaft diameter and handle shell size and thickness constant) the maximum possible coil diameter was 8.5 mm when using a 2mm wire diameter. Further test prototyping found
that a coil diameter of less than 6 mm produced springs that were too stiff for deformation to occur. Thus four different handles each with different spring elements were produced. The corresponding wire and coil diameters are shown in Table 6.2

<table>
<thead>
<tr>
<th>Handle</th>
<th>Wire diameter (d)</th>
<th>Coil diameter (D)</th>
<th>Spring Index (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2.67</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Handle 1 and 4 were chosen to be the stiffest and most flexible respectively. Handles 2 and 3 were selected to be of identical spring index with racket 2 having stiffer springs due to a smaller coil diameter. Two of each handle were manufactured and all handles were attached to a test racket using the assembly method discussed in Section 4.5.4.

The handle sizes for the testing were specified as the Dunlop standard size 3. Sizes 3 and 4 are the most popular handle sizes for players. It was preferable to use a smaller size handle as interviews in the structured relationship model and player discussions found that players preferred to use handles that were too small rather than those that are too big. Studies have used methods to select subjects or rackets related to hand size (Li et al., 2004; Nirschl, 1974), however there is no scientific evidence to validate the measurement of optimal handle size. None of the test subjects reported any discomfort relating to the handle size.

**Test racket configuration**

Rackets were configured to be identical in every possible way. Cosmetically, this was ensured by using identical racket frames, strings and grip wraps, which were wrapped in the same orientation. All buttcaps had a solid piece of plastic placed over the end and covered in black vinyl tape so subjects were unable to feel or identify any differences between the handles.

Attention was directed towards the 'pickup' feel of the rackets, the perception of the racket inertial properties when wielded by the test subjects. It is important that the test subjects were not able to perceive any differences between the moments of the tennis rackets. Differences between rackets reported at impact were to be attributed solely to the handle construction and sensations produced at impact. Slight differences in racket perceptions between the standard and novel handle rackets for those subjects who 'jiggle' the racket to assist in mass discrimination are unavoidable as the flex allowed at the throat region by the handle concept cannot be replicated with the standard racket.

Studies into the effect sizes required for discrimination have generally found that the level of just noticeable difference of a stimulus increase in direct proportion to the magnitude of the stimulus. This
means that the difference threshold is not a constant value. The relationship between the size of the difference threshold and magnitude of the stimulus can be observed using the Weber-Fechner law, in Equation 6.2.

\[
\frac{\Delta R}{R} = k
\]  

(6.2)

Where \( R \) is the reference intensity, \( \Delta R \) the change in stimulus intensity required to satisfy the just noticeable difference (JND), \( k \) is a dimensionless constant known as the Weber fraction, which is generally less than 1 and indicates the proportion by which a standard stimulus must be altered so that the change will be detected 50% of the time (Coren et al., 2004). Although the value has been reported as high as 0.1 for lifting weights (Coren et al., 2004) there are variations in Weber fraction for specific stimulus ranges. Ross & Brodie (1987) determined the Weber fraction for 200 and 400g weights and found a Weber fraction of between 0.08 and 0.09. Since the Dunlop 200G rackets weigh 306g a Weber fraction of 0.085 is used to determine that a maximum tolerance of 26 grammes is acceptable. Efforts to minimise the deviation will be used as the Weber fraction does not account for the effect of skilled or experienced observers. The sensitivity to second moment values has been investigated by Brody (2000). He used a population of experienced tennis players, for detecting changes to the moment of inertia of a tennis racket. For swingweight moment of inertia, a difference of 2.5% between rackets showed that half the players could correctly identify the higher swingweight racket, a quarter could not tell the rackets apart and a quarter of the players incorrectly identified the racket with lower swingweight. Therefore a Weber fraction of 0.025 for experienced tennis players was used for swingweight moment of inertia. For polar moment of inertia, most of the experienced tennis players could distinguish differences in moments of inertia as small as 5% where they began to develop difficulties in differentiating between the rackets. A much higher discrimination threshold for non-players of 10% difference in polar moment of inertia was found. The effects of polar moment are negligible for this testing due to the use of identical racket frames.

To date, no studies determine the ranges of perceptible differences for sporting implements or other similar items. The values of JND from the moment of inertia work by Brody (2000) were applied to the first moment measures to determine that an acceptable tolerance of 2.5% is acceptable for the first moment of the racket. The Weber fractions and acceptable tolerances for the moments of the Dunlop 200G racket are shown in Table 6.3.

<table>
<thead>
<tr>
<th>Moment</th>
<th>200G racket measure</th>
<th>Weber fraction (k)</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero (Weight, g)</td>
<td>306</td>
<td>0.085</td>
<td>26</td>
</tr>
<tr>
<td>First (Balance point, cm)</td>
<td>32</td>
<td>0.025</td>
<td>0.8</td>
</tr>
<tr>
<td>Second (Swingweight, kg·cm²)</td>
<td>281</td>
<td>0.025</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 6.3: Racket moments tolerance values
Table 6.4: Racket moments tolerance values

<table>
<thead>
<tr>
<th>Racket</th>
<th>Handle configuration</th>
<th>Frame Weight (g)</th>
<th>Frame flex (kg·cm²)</th>
<th>Swingweight (kg·cm²)</th>
<th>Balance point (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Standard</td>
<td>306.0</td>
<td>59</td>
<td>281</td>
<td>32.0</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>314.2</td>
<td>54</td>
<td>283</td>
<td>32.3</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>312.2</td>
<td>49</td>
<td>287</td>
<td>32.4</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>312.8</td>
<td>51</td>
<td>287</td>
<td>32.1</td>
</tr>
<tr>
<td>F</td>
<td>4</td>
<td>310.8</td>
<td>43</td>
<td>285</td>
<td>32.3</td>
</tr>
</tbody>
</table>

These values agreed with a major manufacturers tolerances for professional players racket frames, although overall frame weight tolerances are specified much lower at 10 grammes opposed to 26 grammes calculated from the Ross & Brodie (1987) data.

Prior to the commencement of testing, all of the test racket frames were measured using a Babolat RDC to ensure consistency of racket properties. The diagnostic results for each of the test rackets are shown in Table 6.4. Two rackets for each handle condition were assembled to avoid disruption of the testing procedure due to handle failure or snapped strings.

All rackets were strung by the same stringer at a tension of 289 N (60 lbs force) using Dunlop Tour Performance string (gauge = 1.30 mm). The differences in frame flex are caused by the novel handle concepts mounted onto the racket, as the Babolat RDC device requires the handle to be clamped in place for the tip of the frame to be deflected around a support bar. With standard handles, there is little deviation in the racket frame below this support bar. In contrast, the novel handles allow observable deformation of the handle and throat section compared to standard racket frames when measuring frame flex. Experimental modal analysis of each of the strung test rackets was conducted prior to testing to determine the modal frequencies of the rackets. A summary of the test results is shown in Table 6.5. Full description of the procedure used for experimental modal analysis can be found in Appendix D.

Table 6.5: Identified modal frequencies for each of the test rackets (Hz)

<table>
<thead>
<tr>
<th>Racket</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid body mode</td>
<td>38.3</td>
<td>42.2</td>
<td>32.0</td>
<td>32.8</td>
<td>32.8</td>
</tr>
<tr>
<td>1st Bending Mode</td>
<td>123.4</td>
<td>112.5</td>
<td>112.0</td>
<td>110.5</td>
<td>112.5</td>
</tr>
<tr>
<td>2nd Bending Mode</td>
<td>290.7</td>
<td>245.5</td>
<td>258.6</td>
<td>250.0</td>
<td>240.6</td>
</tr>
<tr>
<td>1st Torsional Mode</td>
<td>313.3</td>
<td>306.3</td>
<td>315.6</td>
<td>306.0</td>
<td>290.6</td>
</tr>
<tr>
<td>3rd Bending Mode</td>
<td>567.2</td>
<td>587.5</td>
<td>593.7</td>
<td>593.8</td>
<td>654.7</td>
</tr>
</tbody>
</table>
Test racket order

To combat the lack of initial reference level for subjective measurements, each player was asked to perform the first set of shots during the test with their own racket. This ensured that subjects became accustomed to the test protocol and requirements while using a familiar racket. This initial test was also used to fine tune accelerometer levels and fix minor problems with the test configuration. Each subject tested a maximum number of four rackets, including their own racket. This maximum number of four rackets enabled a test duration of less than 40 minutes per stroke and ensured that subjects would not suffer from boredom, fatigue or pressure of other time commitments. Each subject was required to hit eight shots with each racket for the forehand and volley and five shots for the serve. Respective questions were posed between each shot or test racket.

The test order in which the subjects used the three test rackets was randomised. The order effects of the test rackets are important because the performance rating of a racket is influenced by the rating of a previous racket. These are known as treatment or residual effects. The order for the test rackets is shown in Table 6.6 with each racket being used nine times for each stroke.

Table 6.6: Racket allocation

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Racket test order</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 11</td>
<td>A B C E</td>
</tr>
<tr>
<td>2, 12</td>
<td>A C D F</td>
</tr>
<tr>
<td>3, 13</td>
<td>A D E B</td>
</tr>
<tr>
<td>4, 14</td>
<td>A E F C</td>
</tr>
<tr>
<td>5, 15</td>
<td>A F B D</td>
</tr>
<tr>
<td>6</td>
<td>A B E D</td>
</tr>
<tr>
<td>7</td>
<td>A C F E</td>
</tr>
<tr>
<td>8</td>
<td>A D B F</td>
</tr>
<tr>
<td>9</td>
<td>A E C B</td>
</tr>
<tr>
<td>10</td>
<td>A F D C</td>
</tr>
</tbody>
</table>

6.3.3 Strokes to investigate

Strokes were investigated that occurred frequently in a game situation, and were also suitable for instrumentation. Previous studies have investigated the forehand (Fairley, 1985; Li et al., 2004; Maeda & Okauchi, 2002; Naß & Hennig, 1998; Tomosue et al., 1994), backhand (Hennig et al., 1992; Li et al., 2004; Naß & Hennig, 1998; Walther et al., 2002), and other studies have used test arrangements that cannot be directly compared to a specific type of racket stroke (Iwatsubo et al., 2000; Stroede et al., 1999).

A study by Johnson & McHugh (2006) investigated the performance demands of professional male tennis by examining the number and type of strokes involved in matches at three of the grand slam
tournaments (US Open, French Open, and Wimbledon). For service games (i.e. player serving), the serve was the most frequent stroke (mean = 8.9) than any other type of stroke. Topspin forehand and topspin backhand were the only other strokes that averaged more than one stroke per service game. For return games (i.e. player returning serve) there were more forehand and backhand returns (mean = 2.3 and 3.0) and topspin forehands and backhands (mean = 3.0 and 2.6) per game than any other types of stroke. Between the Wimbledon and French Open, significant differences in the number of strokes were found, likely due to the different playing surfaces. At the French Open there were a higher number of shots per game, accounted for by more topspin forehands and backhands. At Wimbledon there were more forehand and backhand volleys than the two other grand-slam tournaments. Table 6.7 shows a breakdown of the combined tournament data for stroke distribution per game.

Table 6.7: Combined data from three grand slam tournaments on the number of strokes, including one s.d., for service and return games

<table>
<thead>
<tr>
<th>Stroke type</th>
<th>Service games</th>
<th>Return games</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serves</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First</td>
<td>6.4 ±2.9</td>
<td>Returns</td>
</tr>
<tr>
<td>Second</td>
<td>2.5 ±1.9</td>
<td>Fore 2.3 ±1.7</td>
</tr>
<tr>
<td>Topspin</td>
<td></td>
<td>Topspin</td>
</tr>
<tr>
<td>Fore</td>
<td>4.4 ±4.2</td>
<td>Fore 3.0 ±3.4</td>
</tr>
<tr>
<td>Back</td>
<td>3.0 ±3.6</td>
<td>Back 2.6 ±3.1</td>
</tr>
<tr>
<td>Slice</td>
<td></td>
<td>Slice</td>
</tr>
<tr>
<td>Fore</td>
<td>0.2 ±0.8</td>
<td>Fore 0.2 ±0.7</td>
</tr>
<tr>
<td>Back</td>
<td>0.5 ±1.0</td>
<td>Back 0.8 ±1.2</td>
</tr>
<tr>
<td>Half-volley</td>
<td></td>
<td>Half-volley</td>
</tr>
<tr>
<td>Fore</td>
<td>0.2 ±0.5</td>
<td>Fore 0.1 ±0.3</td>
</tr>
<tr>
<td>Back</td>
<td>0.1 ±0.4</td>
<td>Back 0.1 ±0.2</td>
</tr>
<tr>
<td>Volley</td>
<td></td>
<td>Volley</td>
</tr>
<tr>
<td>Fore</td>
<td>0.3 ±0.7</td>
<td>Fore 0.1 ±0.3</td>
</tr>
<tr>
<td>Back</td>
<td>0.4 ±1.0</td>
<td>Back 0.1 ±0.4</td>
</tr>
<tr>
<td>Overhead</td>
<td>0.2 ±0.5</td>
<td>Overhead</td>
</tr>
</tbody>
</table>

Work by Priest et al. (1980b) examined tennis players suffering from elbow pain. The work discovered that 60% of respondents identified the backhand as a painful stroke, with 38% of the respondents citing it as the most painful stroke. The forehand and serve were considered painful strokes by 46% and 45% of subjects respectively, although much lower proportions of 25% and 24% respectively declared these strokes the most painful. Strokes such as the forehand and backhand volley were only found to be painful by 15% and 20%, respectively with only 3% and 7% of respondents found these strokes to be the most painful.

From this work and discussions within the project group, four strokes were investigated; the serve, the forehand, the backhand and the volley. A period of informal pilot testing was conducted to determine suitable ways to instrument subjects and devise protocols for each of the strokes. These preliminary tests highlighted problems with the backhand stroke. Many of the studies into tennis elbow or vibrations from impact that have investigated the backhand stroke (Blackwell & Cole, 1994;
Hennig et al., 1992; Kelley et al., 1994; Knudson, 1991; Li et al., 2004; Naß & Hennig, 1998; Walther et al., 2002) have been focussed on the one-handed backhand. It was quickly apparent in the pilot tests that the majority of current players do not use a single-handed backhand stroke, preferring to adopt a two-handed backhand stroke. Investigation of a two-handed stroke is problematic as it requires both hands to be instrumented as there is currently no evidence to suggest which of the hands is the most dominant for this stroke and which hand is more perceptible to vibration. The investigation of a backhand stroke therefore became logistically unfeasible. For the forehand, pilot tests suggested that players were most comfortable with hitting cross-court forehand strokes from the baseline. Therefore, the cross-court forehand was selected as one stroke to be investigated. Pilot testing for the serve examined various serve varieties. A centreline serve from the right-hand side court (a serve aimed directly down the middle of the court) was selected for test use. For the volley, both forehand and backhand volleys were attempted. Players were found to be more comfortable with forehand volleys and thus this shot was selected for the testing. A brief summary of the strokes selected for testing and a description of the actions performed.

**Cross-court forehand:** Player stands on the baseline and returns ball using forehand stroke to corner of playing area on opposing side of the court.

**Centreline serve:** Player stands on right hand side of court and serve ball into service box, attempting to aim the ball as close to the centreline of the court as possible.

**Forehand volley:** Player stands in at the midway point of the service box and returns the ball to the opposite side service box.

### 6.4 Vibration measurement

As previously mentioned, a number of studies have investigated vibration experienced at impact. In these studies, subject measurement locations have included accelerometer attachment to the bony prominences of the knuckle of the index finger (Fairley, 1985), the back surface of the hand (Maeda & Okauchi, 2002), the Lister tubercle at the wrist (Tomosue et al., 1994), the ulnar head of the humerus at the wrist (Hennig et al., 1992; Li et al., 2004; Naß & Hennig, 1998; Walther et al., 2002), the forearm (Maeda & Okauchi, 2002) and the lateral epicondyle on the elbow (Hennig et al., 1992; Li et al., 2004; Walther et al., 2002). Measures at locations above the hand are predominantly aimed to assess injury potential of the rackets or strokes, as they are unlikely to correlate well with the perception of vibration. Transmissibility to the knuckle of the hand gripping a vibrating handle tends to decrease below unity at frequencies above 100 Hz (Griffin, 1990). Since the sensors in the hand that detect vibration are under the skin and respond to frequencies above 100 Hz (Reynolds & Keith, 1977), the perception of a subject is therefore unlikely to correlate with the measurements of bone
vibration, at regions beyond the hand as there will be little frequency content over a few hundred hertz. Vibration transmission has been shown to be influenced by grip pressure (Hennig et al., 1992), however it was not feasible to require subjects to produce a consistent level of grip pressure as this is unnatural. The measurement of grip pressure was not conducted due to the lack of effective methods to measure the pressure applied by the whole hand and due to the testing requiring multiple rackets, any method had to be mounted to the subjects hand or quick and easy to move onto each racket, which was not available.

6.4.1 Subject measurement

Preliminary tests investigated the use of the wrist as a site for vibration measurements and found that it was not suitable for strokes such as the forehand. The movement required in the wrist for the forehand disrupted accelerometer placement at this location and rendered this location unsuitable. The knuckle of the index finger was found to be the most suitable location for accelerometer placement. At this location there was little flesh to disrupt the vibration measurements, which are accentuated when the subject gripped the racket handle and put the flesh under tension against the knuckle. Subjects did not find the placement of the accelerometer irritating and were able to adjust their grip and execute strokes without noticeable interference. The location of the knuckle was favourable as it was desirable to measure the vibration as close to the fingers as possible to reduce the effects of frequency attenuation away from the fingers. Other locations that were considered included the finger nail of the subject, which has been shown to exhibit unity in vibration transmission up to 1000 Hz (Griffin, 1990). This location was rejected as the positioning of each subjects fingers varies due to handle size, subject’s hand size, and grip technique. Thus the position of the accelerometer is less assured than at the knuckle which is typically positioned directly behind the racket handle at impact. The knuckle measurement site has been used with success (Davies, 2005; Fairley, 1985).

A similar configuration was used by Davies (2005), with a small section of thin stiff plastic (5 x 7 mm) used to steady the accelerometer attachment to the hand. The accelerometer is glued to the plastic to hold it in place and increase the stiffness of mounting. The accelerometer and plastic base are then attached to the measurement site at the knuckle using double sided tape. Davies (2005) used micropore tape on the subject’s skin to prevent irritation from the double-sided tape. The use of micropore was offered to each subject if they possessed concerns with skin irritation, however no subjects requested it to be used. In the preliminary tests, the use of micropore tape reduced the effectiveness of the adhesion of the double sided tape to the site and additional concerns existed over its influence on the skin vibration measurement. An Endevco 25B accelerometer was used for the knuckle site. This piezo-electric accelerometer of mass 0.2 grammes was the lightest accelerometer that could be used for the expected shock range (0-1000g) and a flat frequency response (0-1000 Hz) that was
compatible with the data-acquisition system used. The cables for the accelerometer were passed along the subjects forearm underneath a tubular elastic bandage to help minimise their movement during the strokes. Single-axis vibration measurement was chosen for the knuckle. Although it was desirable to measure vibration about each of the three axes, restrictions on accelerometer mass and available resources constrained measurement to single-axis. This axis was chosen as it is the orientation most frequently used in racket studies and can also be observed to be the axis with predominant force. The attachment sites for the accelerometers are pictured in Figure 6.4.

![Image](a) Knuckle mounting  
(b) Racket mounting

Figure 6.4: The two accelerometer attachment sites

### 6.4.2 Racket measurement

For racket measurement, a location was required that could consistently be used but would not inhibit the subject’s performance of the stroke. ISO5349 covers the placement of accelerometers onto tools for hand-transmitted vibration measurement, with recommendations that the accelerometer should be placed as close to the point of contact between the hand and the implement as possible. Davies (2005) used a mounting attached to the surface of the handle that allowed subjects to grip over the top of the accelerometers. This was the most desirable configuration for racket measurement. However preliminary tests showed that subjects felt that the mounting of an accelerometer beneath the grip was uncomfortable for forehand and serve stroke, due to the motion of the hand during that stroke. An alternative method placed the adapter underneath the grip wrap of the racket handle, therefore reducing the discomfort of the adapter and accelerometers for serve and forehand strokes. However the need for subjects to use more than one racket rendered this an unsuitable solution as it was necessary to swap the adapter and accelerometer between test rackets. It was not feasible to unwrap the grip and replace it each time a racket was used. Consequently the vibration was measured at the racket throat. As all racket frames were identical a landmark on the racket throat for all accelerometers was placed at the same location on each racket. The vibration was measured in the direction of impact as this was the predominant direction of vibration. Similar measurements in golf used a similar arrangement with
vibration, at regions beyond the hand as there will be little frequency content over a few hundred hertz. Vibration transmission has been shown to be influenced by grip pressure (Hennig et al., 1992), however it was not feasible to require subjects to produce a consistent level of grip pressure as this is unnatural. The measurement of grip pressure was not conducted due to the lack of effective methods to measure the pressure applied by the whole hand and due to the testing requiring multiple rackets, any method had to be mounted to the subjects hand or quick and easy to move onto each racket, which was not available.

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an accelerometer attached to the shaft in the direction of impact as it was predominantly sensitive to accelerations occurring as a result of lateral and torsional vibrations of the shaft (Hocknell et al., 1996). An Endevco 2222C accelerometer of mass 1.5 grammes was used for the throat measurement, with shock limit 0–10000g and a flat frequency response (0–1000Hz). The accelerometer was attached to the non-impacting face of the racket using wax and the cable was secured at the edge of the grip wrap using a section of vinyl tape. The accelerometer cable was run along the hand and arm of the subject using the elasticsed tubular bandage to support the cables on the arm. Care was taken to ensure that the racket throat accelerometer cable would not interfere with the knuckle measurement site. The attachment at the throat was favourable because it was flat and could ensure appropriate attachment of the accelerometer.

Both accelerometer cables were clipped to the neck of the subject's top, allowing sufficient cable length in the arm for the subject to execute their stroke. The acceleration cables were then connected to the data acquisition system.

6.4.3 Vibration measurements

The accelerometers were attached to a Brüel and Kjær Nexus conditioning amplifier and then into a 2-channel PC based data acquisition system. The signals were captured and saved using SignalCalc software (Data Physics Inc.). The data was acquired at a sampling rate of 51.2 KHz which produced a resolution of 7.8 Hz. A rectangular window scaling with a low pass filter of 12.5 KHz was used since frequencies over a few-hundred hertz are not likely to be of interest for the vibration study, this value was chosen to prevent aliasing of the chosen sampling rate and to attain data capture length of 128 msec from the trigger point. The data capture was triggered from the racket accelerometer. The results were exported as Matlab data for analysis and interpretation.

6.5 Additional measures

6.5.1 Impact location

The impact location was recorded as it has been shown to be one of the most significant influences on the vibration from impact experienced by a player (Elliott et al., 1980). In particular, data arising from non-proffered impacts by the players was to be preserved to investigate how the racket response is influenced by varying impact locations. Previous studies have either used only impacts rated as preferential (Tomosue et al., 1994; Walther et al., 2002), measured impact locations and rejected data based on impact location tolerances (Roberts et al., 2001), or implemented measures to constrain the impact location (Elliott et al., 1980; Hennig et al., 1992; Li et al., 2004; Maeda & Okauchi, 2002; Noble & Walker, 1994; Stroede et al., 1999).
There have been several methods to determine the impact location. Naß & Hennig (1998) used thin wires wrapped around the strings to allow the contact location of the ball be measured. However, this system was not suitable for the number of rackets to be compared in this study. Hennig et al. (1992) used a laser projected onto the string bed to both guide the test subjects for impact location and to measure actual impact location. This study was conducted using a simulated volley arrangement and was not suitable for the field testing nature of this study. The use of high-speed imagery was considered. However the dynamic nature of the strokes investigated necessitated the use of complicated linked camera arrangements to determine in 3D space the impact location of the ball on the racket frame. A solution was found by Kotze (2005) using dry-wipe marker pens to coat the strings of the racket frame with ink so that the impact location of the tennis ball on the racket could be determined by the region on the string bed where ink was removed. The string bed can be used as a simple grid, and a co-ordinate of the centre of the impact location obtained. This system was selected as it was quick to conduct and could produce results instantaneously. The ink was applied to the strings using a sponge and co-ordinate values for alternating strings were added to the racket frame to allow quick identification of the impact location. A reference circle was produced that could be passed over the string bed to aid in the identification of the centre of the impact location. It was possible to determine the centre of impact even for those impacts where the ball had rolled across the strings (i.e. situations where the ball was hit with spin), as the initial point of contact for the impact location would generally have more ink removed than the areas where the ball contacted as it rolled across and departed the string bed. Figure 6.5 shows an example of ink removed from the string bed by a ball impact.

![Example of ink removed by impact between racket strings and ball](image)

6.5.2 Stroke performance

In tennis testing, unlike sports such as golf, it is difficult to deprive test subjects of the overall shot outcome while using a court test situation. Li et al. (2004); Stroede et al. (1999) conducted test where the subject was unable to see the racket at impact. In these tests, the subject’s hand and racket were static prior to impact. Subjects are briefed at the start of the test to ignore the shot
results and impact location when developing their perception ratings. They were instructed to base the ratings solely on the kinaesthetic feedback received from impact. A concern was that subjects may become influenced by their shot outcome and rate the rackets which produced more successful strokes more favourably than those that didn’t. The purpose of this testing was to investigate how the racket measures of vibration influence subject perceptions and therefore the effect of how successful the racket is for each shot was not important. To compensate for the possibility of subjects being influenced by racket performance shot performance of each subject was measured so that possible correlations between subjective ratings and shot performance could be investigated during the results analysis. Methods of rating subject performance for tennis skills have been conducted previously using Hewitt’s tennis achievement test (Hewitt, 1966). However a scoring system that has been commonly used by the University’s exercise physiology program to monitor shot outcome, also used by Steele (2006), was chosen, as it was the simplest to implement and required no additional resources. A second investigator responsible for feeding the balls to the player was able to score the shot performance after each shot. The court was arranged for each shot as shown in Figure 6.6. The dimensions of each target area are $2.5 \times 2$ metres.

![Figure 6.6: Shot scoring locations for each of the test strokes](image)

### 6.6 Test parameters

This section discusses the remaining factors of the test protocol including the test venue, the ball supply, and the participant selection.

#### 6.6.1 Ball supply

Slazenger Wimbledon High-Vis balls were selected for this study. Two tubes (6 balls) were used for each subject and stroke to ensure that the balls were consistent and the effects of degradation and pressure loss were minimised. The balls were delivered to the subject using a BOLA ball cannon. This device is operated by two large rotating wheels that force the ball through a small aperture upon launching. Both wheels were operated at the same velocity to ensure no spin was imparted to the ball. This device was chosen as it was much more consistent than alternative tennis training ball machines. The muzzle velocity of the BOLA was set at $23 \text{ ms}^{-1}$, an appropriate groundstroke speed for both men’s and women’s game (Haake & Goodwill, 1997; Steele, 2006; Stroede et al., 1999).
Since, it was not possible to control the exact position that the subjects impacted the ball, there were slight unquantifiable deviations in the ball velocity at the point of impact. For the forehand, this was influenced by the point at which the subjects chose to hit the ball after the bounce. For the volley, the height of the ball over the net varied depending on the stature and preference of the subjects. Although attempts were made to control the distance from the baseline and net at which subjects impacted the ball for forehand and volley strokes respectively, subjects tended to adjust their position at ball impact instinctively. For the serve there was no control of the inbound velocity of the ball as this was approximately zero. The resultant velocities of the serves were also not quantified.

6.6.2 Court setup

All of the tests were conducted in Loughborough University's indoor tennis facility using acrylic hard court surfaces. The use of an indoor court allows climate effects to be consistent across all trials. There was no attempt made to control the ambient temperature of the courts, as subjects completed their tests for each stroke within a single test session, and the temperature deviations between the various test sessions were not significant. Inter-subject differences are more likely to be caused by physiological differences and technique than through the effect of varying ambient temperature for each subject.

6.7 Participant selection

The test subjects were selected from the Loughborough University men’s and women’s first and second tennis teams, a highly competent standard. The mean ± s.d. age of the players was 20.4 ± 1.7 years, with an average of 12.7 ± 2.7 years playing experience. Meilgaard et al. (1999) suggests a minimum of eight subjects for sensory evaluations. More experienced players were preferred as they were considered to provide more competent judges of sensation received at impact. The test procedure was approved by Loughborough University’s Ethical Approval Board. Eight male and seven female subjects were selected for testing each stroke. Unfortunately, due to injuries, other commitments and equipment failure only 14 subjects were tested for the forehand, 13 for the serve and 12 for the volley. None of the subjects reported previous experience of tennis elbow, ensuring no concerns regarding varied vibration sensitivity. All of the subjects were right handed except for one male subject who was left handed. The court setup was therefore reversed for this subject so that the same stroke was performed as the other subjects.
Chapter 7

Analysis of novel handle concept: Results

A large scale study was conducted examining quantitative and qualitative measures of racket performance for three different tennis strokes: cross-court forehand, serve and forehand volley. The results of this study aimed to examine the performance of a novel handle concept, compare the differences between racket strokes and determine racket characteristics responsible for influencing subjective perceptions. The results of this study are documented in this chapter.

7.1 Analysis procedure

A total of 1028 shots were analysed in this testing: 448 shots for the cross court-forehand (forehand), 260 shots for the serve (serve) and 320 shots for the forehand volley (volley). Due to test withdrawals and equipment problems, not as many subjects were tested as initially proposed, however sufficient data was collected to perform meaningful analysis of the results of each stroke. The results were grouped by subject, racket used, and stroke performed. All objective results were plotted and erroneous results were removed from the data.Erroneous results were caused by several factors: impacts with double peaks caused by instances when the accelerometer may have become unattached from the measurement site during the impact, recorded impacts where the data trigger was activated before the actual impact, and other reasons which may have inexplicably produced unusual vibration traces.

The results are presented so that comparisons of how the shot type affects the results can be observed and where possible statistical analysis has been conducted to determine any trends. The first stage of analysis examined the four subjective characteristics and the ratings provided.

7.2 Analysis of subjective data

Statistical analysis of each subject's results was conducted without modifying their rating data, however when comparing overall racket ratings, data was standardised to account for different scales used
by various subjects. The results demonstrate that the subjects possess no common reference rating scale relative to one another, this problem was overcome by standardising the data (Roberts, 2002). For each player and feel characteristic, the mean and standard deviation of their ratings were calculated. Individual ratings were then standardised by subtracting the mean of the rating from the original value, and then dividing the result by the standard deviation of the ratings.

For each feel characteristic, the standardised ratings for each player have a mean of zero and a standard deviation of one, with the orientation of the scales maintained as positive to negative values for control, power, feel and vibration. To investigate correlations between the subjective characteristic ratings, the Spearman correlation was used given non-parametric conditions and the inability to assume that a linear relationship between factors was present.

7.2.1 Cross-court forehand

Table 7.1: Mean ±s.d. standardised subjective forehand results

<table>
<thead>
<tr>
<th>Racket</th>
<th>Control</th>
<th>Power</th>
<th>Feel</th>
<th>Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>B†</td>
<td>-0.36 ±0.92</td>
<td>-0.28 ±0.74</td>
<td>0.19 ± 0.96</td>
<td>0.33 ±1.01</td>
</tr>
<tr>
<td>C‡</td>
<td>0.05 ±0.54</td>
<td>-0.53 ±0.73</td>
<td>-0.01 ±0.81</td>
<td>-0.01 ±0.91</td>
</tr>
<tr>
<td>D†</td>
<td>0.11 ±0.85</td>
<td>-0.28 ±0.68</td>
<td>0.31 ±0.75</td>
<td>0.14 ±0.76</td>
</tr>
<tr>
<td>E‡</td>
<td>0.23 ±0.67</td>
<td>-0.21 ±0.74</td>
<td>-0.04 ±0.62</td>
<td>0.09 ±0.80</td>
</tr>
<tr>
<td>F†</td>
<td>-1.04 ±0.47</td>
<td>0.03 ±1.07</td>
<td>0.10 ±1.16</td>
<td>0.85 ±0.73</td>
</tr>
</tbody>
</table>

† n = eight subject comparisons
‡ n = nine subject comparisons

Figure 7.1 shows a comparison of the subjective responses for each characteristic and test racket used, with the mean standardised values included in Table 7.1. The large variations in inter-subject preferences produces large standard deviations in the overall values. Analysing the player subjective response data, a few significant correlations between different feel characteristics were observed, although no consistent pattern emerged. This is in part due to the small data size requiring perfect correlation between the factors to produce significant correlations. To increase the sample data size, Spearman correlation analysis of all of the ratings for each racket was conducted. From these results the only significant relationship was observed in Racket B (the standard racket), where the relationship between mean standardised vibration rating and standardised power rating (Spearman, $r^2 < 0.7$, $p < 0.05$), suggests that as vibration increased, the rating of racket power decreased and vice versa.

Table 7.2 shows the Spearman correlation for all ratings and rackets during forehand tests. The only significant relationship found is the negative correlation between the standardised rating of racket control and the mean standardised rating of vibration (Spearman, $r^2 < 0.6$, $p < 0.01$). This suggests that as the perceived level of vibration increases, the perceived control of the racket decreases. Using two-way independent analysis of variance (ANOVA) to investigate significant differences between the
subjective ratings, two significant differences emerged. For the rating of power, racket F was found to be rated significantly lower ($F(4,37)=4.251$, $p < 0.05$) than all other novel racket designs. In addition, significant differences were found between racket F (least stiff springs) and the all the other test rackets for vibration rating ($F(4, 294)=13.638$, $p < 0.05$), with F producing the highest vibration rating.
Figure 7.1: Forehand test subject ratings for subjective characteristics for each racket used, bars indicate 1 s.d. where used.
Table 7.3: Mean ±s.d. standardised subjective serve results for each racket

<table>
<thead>
<tr>
<th>Racket</th>
<th>Control</th>
<th>Power</th>
<th>Feel</th>
<th>Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>B†</td>
<td>-0.14 ±0.88</td>
<td>-0.23 ±1.01</td>
<td>-0.08 ±0.86</td>
<td>-0.07 ±1.05</td>
</tr>
<tr>
<td>C‡</td>
<td>-0.52 ±0.80</td>
<td>-0.45 ±0.86</td>
<td>0.47 ±0.85</td>
<td>0.49 ±0.81</td>
</tr>
<tr>
<td>D‡</td>
<td>-0.06 ±0.97</td>
<td>0.52 ±0.59</td>
<td>0.09 ±0.92</td>
<td>-0.02 ±0.98</td>
</tr>
<tr>
<td>E†</td>
<td>0.54 ±0.58</td>
<td>-0.12 ±0.84</td>
<td>-0.21 ±0.66</td>
<td>-0.27 ±1.02</td>
</tr>
<tr>
<td>F†</td>
<td>-0.34 ±0.91</td>
<td>0.30 ±0.35</td>
<td>-0.33 ±0.86</td>
<td>0.44 ±0.80</td>
</tr>
</tbody>
</table>

† n = seven subject comparisons
‡ n = eight subject comparisons

Table 7.3 shows the mean standardised ratings for each of the subjective characteristics and Figure 7.2 compares the responses to each of the test rackets by the individual subjects. Again, no patterns emerged with the subjects' correlations, and only a few subjects demonstrated any correlations between their subjective results. The same trend was observed between rackets, although further analysis indicated a correlation in Racket C between standardised subjective racket feel and standardised subjective racket control (Spearman, $r^2$ < -0.8, $p$ < 0.05) suggesting that as the perceived flexibility of the racket increased, the control of the racket decreased. For Racket E there was a negative correlation between mean standardised perceived vibration and standardised racket control (Spearman, $r^2$ < -0.8, $p$ < 0.05).

Table 7.4 shows the Spearman correlation between all the subjective characteristics ratings for the serve. Across all the rackets a negative correlation was found between the standardised control rating and mean standardised rating of impact vibration (Spearman, $r^2$ < -0.5, $p$ < 0.01). Again, a two-way independent ANOVA was used to examine the subjective results and no significant differences were found between the ratings of power, control and feel. For the vibration rating, significant differences ($F(4,144)$ = 7.779) were found with racket C overall producing significantly lower values than racket F.

Table 7.4: Overall Spearman subjective correlations for serve

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Vibration</th>
<th>Feel</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>-0.50†</td>
<td>-0.19</td>
<td>-0.08</td>
</tr>
<tr>
<td>Power</td>
<td>0.01</td>
<td>-0.14</td>
<td></td>
</tr>
<tr>
<td>Feel</td>
<td>-0.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† significant at 0.01 level
n = 36 comparisons
Figure 7.2: Serve test subject ratings for subjective characteristics for each racket used, bars indicate 1 s.d. where used.
7.2.3 Forehand volley

Table 7.5: Mean ± s.d. standardised subjective volley results for each racket

<table>
<thead>
<tr>
<th>Racket</th>
<th>Control</th>
<th>Power</th>
<th>Feel</th>
<th>Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.16 ±0.86</td>
<td>0.26 ±0.79</td>
<td>-0.06 ±0.72</td>
<td>-0.19 ±0.81</td>
</tr>
<tr>
<td>C</td>
<td>0.82 ±0.68</td>
<td>0.61 ±0.44</td>
<td>0.33 ±1.00</td>
<td>-0.03 ±0.95</td>
</tr>
<tr>
<td>D</td>
<td>0.08 ±0.54</td>
<td>-0.62 ±0.84</td>
<td>0.40 ±0.74</td>
<td>0.11 ±0.93</td>
</tr>
<tr>
<td>E</td>
<td>-0.07 ±0.81</td>
<td>0.37 ±0.49</td>
<td>-0.03 ±0.79</td>
<td>0.08 ±0.94</td>
</tr>
<tr>
<td>F</td>
<td>-0.55 ±0.97</td>
<td>-0.79 ±0.86</td>
<td>-0.57 ±1.09</td>
<td>0.40 ±0.87</td>
</tr>
</tbody>
</table>

* n = five subject comparisons
° n = six subject comparisons
† n = seven subject comparisons
‡ n = eight subject comparisons

Results for the mean standardised subjective ratings can be found in Table 7.5 and Figure 7.3. There were no patterns of correlation amongst the subject ratings for the four subjective characteristics. The analysis of the racket specific ratings showed few correlations with the exception of racket C. A correlation between mean standardised vibration rating and standardised rating of racket feel was observed (Spearman, \( r^2 > 0.9, p < 0.05 \)), suggesting that an increased level of perceived vibration resulted in perception of a less flexible racket.

Table 7.6 shows that there were no significant correlations for the overall stroke comparisons using Spearman correlation. Two-way independent ANOVA comparisons again indicated that overall racket F produced significantly smaller power ratings than racket C (\( F(4, 28)=4.723 \)). For the vibration rating, racket F was again found to produce significantly higher ratings than racket B (\( F(4, 231)=3.667 \)).

Table 7.6: Overall Spearman subjective correlations for forehand volley

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Vibration</th>
<th>Feel</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>-0.16</td>
<td>0.18</td>
<td>0.24</td>
</tr>
<tr>
<td>Power</td>
<td>-0.26</td>
<td>-0.12</td>
<td></td>
</tr>
<tr>
<td>Feel</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n = 33 comparisons
Figure 7.3: Volley test subject ratings for subjective characteristics for each racket used, bars indicate 1 s.d. where used.
7.2.4 Consistency of subject responses

The consistency of the subjects' ratings was tested using Kendall's coefficient of concordance ($W$) (Durbin, 1951; Siegel & Castellan, 1988). The coefficient of concordance allows the preference of a group of observers or raters to be investigated when they have ranked the objects in order of preference. Although subjects did not provide ranking of the rackets directly, they did provide scale values which were then standardised and used to produce ordered rankings of the rackets for each characteristic.

The measure of concordance is useful as it provides a measure of the consistency of responses amongst the subjects. Durbin (1951) provides the methodology for using the Kendall coefficient of concordance for measures using incomplete blocks, sets of data where not every object is rated by every subject, but each object is rated an equal number of times. The results of the Kendall coefficient of concordance measures are shown in 7.7.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Shot type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forehand</td>
</tr>
<tr>
<td>Control</td>
<td>0.533†</td>
</tr>
<tr>
<td>Power</td>
<td>0.056</td>
</tr>
<tr>
<td>Feel</td>
<td>0.093</td>
</tr>
<tr>
<td>Vibration</td>
<td>0.430†</td>
</tr>
</tbody>
</table>

† significant at 0.05 level
‡ significant at 0.1 level

For the control characteristic, significant values for both forehand and volley strokes are found. In addition, the rating of level of vibration show significant agreement for forehand and serve. Only the volley produced significant agreement amongst the subjects for power rating. The feel rating characteristics did not produce significant concordance values for any strokes, possibly suggesting that the appraisal of this characteristic is unfamiliar to subjects and thus each subject determines this value based on different racket properties, resulting in lack of agreement between the ratings.
7.3 Analysis of objective data

7.3.1 Impact location

The impact locations were measured using the stringbed as a simple grid, as discussed in Section 6.5.1, with the geometric centre of the string bed being a point at (10, 9). The stringbed measures do not provide exact positions of impact as the measurement resolution is limited by the distance of string separation. However, it offers a fast effective method to determine approximate impact location. Measurements of the string bed for the test rackets show that within the central area of the stringbed, the spacing of the strings is relatively constant with one unit in the $x$ direction corresponding to 11 mm and one unit in the $y$ direction corresponding to 15 mm (Figure 7.4).

![Figure 7.4: Diagram of reference grid used to determine impact location measurements](image)

Prior to analysis of the measured vibration data the impact location data was analysed. Several studies have demonstrated that the impact location provides a significant influence on the vibration experienced by the player at impact (Elliott et al., 1980). Repeated measures ANOVA analyses were performed to determine whether any significant differences existed between impact locations and the rackets used for each shot type and if any significant differences existed between the impact location and shot type. Table 7.8 shows the mean impact locations from all subjects for each stroke type.

Analysis of all the impact locations was conducted, significant differences were found for both the $x$ and $y$ axis impact locations between stroke type ($F(1.0, 265.3)=110, p<0.05$) and ($F(1.0, 264.7)=120, p<0.05$), respectively.

<table>
<thead>
<tr>
<th>Stroke</th>
<th>$x$-axis</th>
<th>$y$-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehand</td>
<td>9.7 ±2.2</td>
<td>9.6 ±2.1</td>
</tr>
<tr>
<td>Serve</td>
<td>9.1 ±2.6</td>
<td>9.6 ±1.9</td>
</tr>
<tr>
<td>Volley</td>
<td>11.5 ±2.4</td>
<td>10.1 ±2.3</td>
</tr>
</tbody>
</table>

The impact locations for each racket and stroke were also examined, using a two-way independent ANOVA. Table 7.9 shows the mean impact locations for each test racket for each stroke. Significant differences ($p<0.05$) between subjects impact locations $x/y$ were observed for the forehand, serve and...
volley strokes $F(13,294)=4.439/3.584$, $F(11,144)2.687/4.758$, $F(10,231)=2.598/7.334$. No significant
differences were found between the racket impact locations for the forehand and volley. The serve stroke
exhibits no significant differences between rackets for the $x$-axis impact location, $F(4,144)=1.108$, but
significant differences exist for the $y$-axis impact locations $F(4,144)=1.424$, $p < 0.05$. Impact locations
on the $y$-axis were statistically greater for racket E than racket C and D.

| Table 7.9: Mean impact location for each racket |
|-----------------|-------|-----------------|-------|
| Racket         | Forehand impact | Serve impact | Volley impact |
|                | $x$-axis | $y$-axis | $x$-axis | $y$-axis | $x$-axis | $y$-axis |
| B              | 9.9 ±2.4 | 9.2 ±2.1 | 9.3 ±2.4 | 9.6 ±1.7 | 10.9 ±2.0 | 10.3 ±2.2 |
| C              | 9.6 ±2.2 | 9.6 ±2.1 | 9.4 ±3.2 | 9.4 ±2.1 | 12.2 ±2.3 | 9.8 ±2.0 |
| D              | 9.6 ±1.9 | 9.7 ±1.9 | 8.3 ±2.4 | 9.2 ±1.6 | 11.3 ±2.3 | 10.4 ±2.3 |
| E              | 9.8 ±2.2 | 9.8 ±2.1 | 9.5 ±1.5 | 10.4 ±1.7 | 12.0 ±2.6 | 10.1 ±2.7 |
| F              | 9.7 ±2.4 | 10.0 ±2.3 | 9.1 ±3.2 | 9.4 ±2.1 | 11.3 ±2.5 | 9.6 ±2.2 |

Using a repeated measures ANOVA, comparisons of the impact locations demonstrated few signif­
icant differences between various test rackets for the individuals. These results suggest that generally
subjects did not produce variable impact locations with different rackets. Comparing all impact loca­
tions for each stroke, there was so significant difference for impact locations between the test rackets,
but there were significant differences between individual’s impact locations for each of the strokes.
For all strokes the greatest number of significant differences between individuals impact locations
were found with $y$-axis measures. Of all strokes, the volley ($F(10,230)=6.954$ and $F(10,230)=11.647$,
$p < 0.05$ for $x$ and $y$-axis respectively), was found to produce the most significant differences between
subjects impact locations, followed by the serve ($F(11,154)=8.702$ and $F(11,154)=11.250$, $p < 0.05$
for $x$ and $y$-axis respectively) with the forehand ($F(12,264)=2.854$ and $F(12,264)=6.197$, $p < 0.05$
for $x$ and $y$-axis respectively) demonstrating the least significant differences. Table 7.10 shows the mean
impact locations for each shot type for each test subject.

The coefficient of variance (CV) of the impact locations for each stroke type is shown in Table 7.11.
Coefficient of variance is used to provide a measure of dispersion of the measured data. It can be used
to determine the precision of the subjects’ performance where values range from 0–1 and a lower CV
value represents a subject who produced more consistent impact locations.

The coefficient of variance results suggest that the $x$ impact location was least dispersed amongst
the volley and most dispersed using the serve. For $y$-axis impact locations the serve was found
to produce the least dispersion. Most players achieved a CV of less than 0.25 with only a small
number of subjects producing values above that level. No subject exceeded that level for both axes
measurements. The mean values of CV reflect a general consistency in impact location for all three
strokes which may be a reflection of subject ability level with even more skilled subjects producing
lower CV values and less-skilled subjects producing higher CV values. Higher variance in impact location was observed with the x-axis compared to y-axis. This is likely due to subjects attempting to impact the ball as close to the long axis of the racket as possible to prevent the racket twisting at impact, with players less concerned with the position of impact along the x-axis, producing larger variability in impact locations along this axis.

For the purposes of data analysis rejection criteria were not used to exclude test impacts due to impact location as has been done with previous impact location studies (Roberts, 2002). This route was chosen as it was of interest to study the impact perceptions and vibration of off-centre as well as central-impacts. Thus all impact data was preserved unless other data recording issues resulted in rejection of certain measurements. Plots of the individual subjects impact locations for each stroke can be found in Appendix F.
Table 7.11: Subject coefficient of variance (CV) of impact location for each stroke performed

<table>
<thead>
<tr>
<th>Subject</th>
<th>Forehand</th>
<th>Serve</th>
<th>Volley</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>1</td>
<td>0.19</td>
<td>0.23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.18</td>
<td>0.19</td>
<td>0.27</td>
<td>0.13</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
<td>0.17</td>
<td>0.37</td>
<td>0.15</td>
</tr>
<tr>
<td>4</td>
<td>0.21</td>
<td>0.20</td>
<td>0.24</td>
<td>0.17</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>0.20</td>
<td>0.22</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>0.20</td>
<td>0.28</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.24</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>8</td>
<td>0.23</td>
<td>0.22</td>
<td>0.29</td>
<td>0.12</td>
</tr>
<tr>
<td>9</td>
<td>0.13</td>
<td>0.13</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>10</td>
<td>0.24</td>
<td>0.20</td>
<td>0.32</td>
<td>0.18</td>
</tr>
<tr>
<td>11</td>
<td>0.28</td>
<td>0.22</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>12</td>
<td>0.12</td>
<td>0.19</td>
<td>0.26</td>
<td>0.14</td>
</tr>
<tr>
<td>13</td>
<td>0.19</td>
<td>0.12</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>14</td>
<td>0.25</td>
<td>0.19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean</td>
<td>0.21</td>
<td>0.20</td>
<td>0.23</td>
<td>0.15</td>
</tr>
</tbody>
</table>
7.3.2 Shot performance

A simple shot scoring method was used to examine subject performance with each racket. Shots scored two points for landing within the target area, one point for landing in an area close to the target, zero points for all balls landing away from the target area, and minus one point for shots failing to cross the net. The target areas for each stroke are shown in Section 6.5.2. The influence of subject knowledge of shot outcome is difficult to avoid and it can influence subjective ratings of racket properties. This data was recorded to be used to examine racket differences or explain subjective ratings. Table 7.12 shows the mean results for each racket and each shot type.

Table 7.12: Mean shot performance scores for each racket and overall stroke

<table>
<thead>
<tr>
<th>Racket</th>
<th>Forehand</th>
<th>Serve</th>
<th>Volley</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.78</td>
<td>0.46</td>
<td>0.95</td>
</tr>
<tr>
<td>C</td>
<td>1.30</td>
<td>0.40</td>
<td>1.35</td>
</tr>
<tr>
<td>D</td>
<td>0.92</td>
<td>0.51</td>
<td>1.11</td>
</tr>
<tr>
<td>E</td>
<td>1.23</td>
<td>0.86</td>
<td>1.18</td>
</tr>
<tr>
<td>F</td>
<td>1.08</td>
<td>0.57</td>
<td>1.17</td>
</tr>
<tr>
<td>Mean</td>
<td>1.07</td>
<td>0.58</td>
<td>1.14</td>
</tr>
</tbody>
</table>

A two-way independent ANOVA was used to investigate significant differences for each stroke in shot performance amongst the test rackets. For the forehand and serve, no significant differences in shot performance between subjects or rackets was found. For the volley, significant differences were found between subjects, $F(10,231)=3.651, p < 0.001$, but no significant differences were found between the racket's performance, $F(4,231)=0.349, p > 0.05$. The results in Table 7.13 show that overall players were most accurate with volleys, and least accurate with serves.

The mean shot performance scores for each stroke for the test subjects is also shown in Table 7.13. A repeated measures ANOVA was used to investigate shot performance, and no significant differences were found between the shot performances of each of the test rackets used by each subject.
Table 7.13: Mean shot performance scores for each subject for each stroke

<table>
<thead>
<tr>
<th>Racket</th>
<th>Forehand</th>
<th>Serve</th>
<th>Volley</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.96</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>0.33</td>
<td>1.42</td>
</tr>
<tr>
<td>3</td>
<td>0.92</td>
<td>0.60</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>1.38</td>
<td>0.47</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.63</td>
<td>0.73</td>
<td>1.04</td>
</tr>
<tr>
<td>6</td>
<td>0.88</td>
<td>0.20</td>
<td>0.88</td>
</tr>
<tr>
<td>7</td>
<td>0.92</td>
<td>1.00</td>
<td>1.25</td>
</tr>
<tr>
<td>8</td>
<td>0.92</td>
<td>0.93</td>
<td>0.58</td>
</tr>
<tr>
<td>9</td>
<td>1.46</td>
<td>0.27</td>
<td>1.42</td>
</tr>
<tr>
<td>10</td>
<td>1.33</td>
<td>0.20</td>
<td>1.25</td>
</tr>
<tr>
<td>11</td>
<td>1.00</td>
<td>0.33</td>
<td>1.63</td>
</tr>
<tr>
<td>12</td>
<td>1.42</td>
<td>0.87</td>
<td>1.17</td>
</tr>
<tr>
<td>13</td>
<td>1.04</td>
<td>1.00</td>
<td>1.38</td>
</tr>
<tr>
<td>14</td>
<td>1.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean</td>
<td>1.07</td>
<td>0.58</td>
<td>1.14</td>
</tr>
</tbody>
</table>
7.3.3 Vibration measures

Two measurements of vibration were taken during the testing, located at the racket throat and the first knuckle of the subject’s gripping hand. An example of a typical vibration trace from these two locations is shown in Figure 7.5.

![Vibration Trace Graph](image)

Figure 7.5: Example of a typical vibration measure from testing

As expected, the racket vibration trace is much larger in magnitude compared to the knuckle vibration trace due to the attenuation of vibration between these two measurement points. The peak in the racket vibration trace indicates the impact of the ball with the racket. A delay in the peak vibration between the racket and knuckle vibration trace can also be observed, corresponding to the time taken for the vibration energy to propagate from the point of impact on the racket to the hand, approximately 4 ms (Casolo et al., 2000; Cross, 1999; Engel, 1995; Hatze, 1976; Maeda & Okauchi, 2002).

To quantify the vibration levels of the traces, the root mean square (rms) of the vibration trace was used. The rms value provides an arithmetic mean of the vibration trace and is a common method for evaluating vibration or wave signals. The duration of vibration exposure can significantly influence human responses. Griffin (1997) suggests that rms acceleration may not provide a good indication of vibration severity if the vibration is intermittent, contains shocks, or varies in magnitude from time to time. Three rms measures of the vibration traces were made: full-trace rms (RMS), short-duration rms (SRMS), and maximum rms (MaxRMS). The RMS value is the rms measure of the entire vibration trace from the zero time point (i.e. point of impact). The short-duration SRMS value corresponds only to the rms of the vibration trace between 0 and 0.02 seconds, corresponding to the majority of the vibration energy from impact. MaxRMS is the maximum absolute rms vibration found within
the first 0.03 seconds of the vibration trace. The MaxRMS value is calculated using a window of 1 ms for measurement. Figure 7.6 show plots of each racket’s mean rms measures, with Appendix E showing the individual’s mean results with each racket for all the rms measures, were the high standard deviation values for the mean racket measures can be seen to be caused by a large variation in the performance of the test rackets with each subject.

The rms measures were analysed using two-way independent ANOVA to investigate the differences ($p < 0.05$) between subjects results and the differences between all the results for each test racket used, Bonferroni post-hoc tests were used to reveal the significant pairwise comparisons. Repeated measures ANOVA were conducted on the results for each racket used by each subject and significant differences ($p < 0.05$) between rackets have been highlighted using * above both the corresponding rackets for Figures E.1 - E.3. A synopsis of the results for each of the rms measures is provided in the following section.

**RMS measures** The RMS results showed that for all strokes, significant differences existed between the subjects with both vibration measurements. For the forehand measures, racket B was found to be significantly higher than the rest of the rackets for racket throat vibration measures. Analysing knuckle vibration measures found that racket C produced significantly greater magnitude RMS than rackets B and F. Significant differences were also found for the serve between racket throat vibration measures for the test rackets ($F(4,143)=2.877$), with a significantly lower RMS for racket F than rackets B and C. For knuckle vibration measures, there were significantly lower measures for racket B than all other rackets. The volley results showed that for racket throat measures racket D was significantly lower than the other rackets. For knuckle vibration measures, racket B was again significantly lower than all other rackets ($F(4,231)=2.861$), though there was no significant differences between rackets B and D.

**SRMS measures** Since SRMS results exhibited much the same trends as the RMS results, only the trends that differed are discussed. For the forehand measures, significant differences between racket B and C were found for the knuckle vibration. Examining serve results, significantly greater magnitude racket throat measures were observed for racket B compared to rackets D and F. For knuckle measures no significant differences were found, except that racket F was significantly higher in magnitude than racket E. Results for the volley followed the significant trends observed with RMS measures.

**MaxRMS measures** Examining the forehand stroke MaxRMS values, racket throat measures revealed significant differences between the rackets ($F(4,271)=2.780$) with racket B producing significantly higher values than the rest of the test rackets. The only significant differences in knuckle measures were found between the larger values of racket C and those of racket F. Analysis of the serve
results showed significant differences between the rackets for both the racket throat and knuckle measures $F(4,143)=2.576$ and $F(4,143)=3.854$. Racket B had significantly greater racket throat measures than rackets D, E and F. For the knuckle measures, again the only significant difference found racket F to be greater than racket E. Significant differences were also discovered between racket throat and knuckle MaxRMS measures for the volley ($F(4,231)=4.095$ and $F(4,227)=3.608$ respectively). For the racket throat measures, significant differences were found between the larger measures of racket B and the other test rackets and significant differences were also found between the lowest measures of racket D and those of racket E. For the knuckle measures racket F was significantly greater than rackets B, D, E and racket B was found to be significantly lower than rackets C and E.

In general rms results show that for the throat measure racket B is of higher magnitude than the other test rackets, regardless of stroke. However, for knuckle measures, racket B is significantly lower than at least one of the rackets for RMS and SRMS measures. Racket F is also found for various strokes to be significantly higher magnitude rms measures than several of the rackets at both measurement sites.
Figure 7.6: Plot of the mean racket results for each of the rms measures (bars represent ± 1 s.d.)
7.3.4 Damping ratio

The rate at which the vibration experienced by the subject and racket decreased was also examined. Studies have used a variety of measures to investigate the decay of vibration including the log decrement of the vibration (Carroll, 1985; Maeda & Okuchi, 2002), curve fits to the data to examine the curve gradient, and damping characterisation. In these studies, the nature of the vibration traces recorded were not suited to the curve-fitting to measure decay unlike the more sinusoidal vibration traces produced by freely suspended rackets (Carroll, 1985). A method was developed to measure the amount of vibration reduced over a given time period, termed the damping ratio (Equation 7.1)

\[ D_{\text{Ratio}} = \frac{RMS_{10}}{RMS_{\text{MAX}}} \]  

(7.1)

where \( RMS_{\text{MAX}} \) is the max rms value of the absolute vibration measured using a 1 ms window and \( RMS_{10} \) is the value of rms vibration measured using a 1 ms window at a position 10 ms from the measurement of the \( RMS_{\text{MAX}} \). Thus \( D_{\text{Ratio}} \) expresses the amount of the max vibration remaining after 10 ms from the measured maximum. Table 7.14 shows the damping ratio for each of the test rackets and strokes.

Table 7.14: Comparison of damping ratio measures ± s.d. for each test racket

<table>
<thead>
<tr>
<th>Racket</th>
<th>Racket measures</th>
<th>Knuckle measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forehand</td>
<td>Serve</td>
</tr>
<tr>
<td>B</td>
<td>0.18 ±0.09</td>
<td>0.19 ±0.09</td>
</tr>
<tr>
<td>C</td>
<td>0.24 ±0.07</td>
<td>0.23 ±0.10</td>
</tr>
<tr>
<td>D</td>
<td>0.19 ±0.06</td>
<td>0.21 ±0.11</td>
</tr>
<tr>
<td>E</td>
<td>0.20 ±0.10</td>
<td>0.19 ±0.06</td>
</tr>
<tr>
<td>F</td>
<td>0.18 ±0.07</td>
<td>0.17 ±0.07</td>
</tr>
<tr>
<td>Overall</td>
<td>0.20 ±0.08</td>
<td>0.20 ±0.09</td>
</tr>
</tbody>
</table>

To examine the damping ratios experienced by each test subject, the results are split into values representing each subject’s mean results with each test racket used (Figure E.4).

A two-way independent ANOVA was used to compare the subject and racket results for each of the strokes. Significant differences \((p < 0.05)\) were discovered between the subjects for both measurement locations with each stroke, except for knuckle damping ratio measures for the volley and the racket throat damping ratios for the serve where high variations in the measures may have made significant differences difficult to establish. With each stroke, significant differences were found between the racket damping measures of the various test rackets. For the knuckle damping measures, no significant differences were found between the rackets. For the forehand, significant differences were found between the rackets for racket throat measures \((F(4,271)=5.952)\) with significantly greater measures for racket C than rackets B, D and F. The serve stroke produced significant differences between the rackets for
the racket throat measures ($F(4,143)=2.749$) with racket C observed to be significantly greater than racket F. The volley racket results indicated that racket C was significantly greater than rackets B and F, $F(4,231)=6.506$.

![Figure 7.7: Racket damping ratio measures (bars represent ± 1 s.d.)](image-url)
7.4 Correlation of subjective with objective measures

For each stroke the correlation of subjective measures and objective measures was investigated to determine how the racket response from impact influences player’s perception. Spearman correlation was again used. The correlations found between individual measures do not appear to follow any consistent trends, with different correlations between the measures for each individual. Due to the small sample size, it is difficult to form significant correlations. Therefore, tests were conducted for individual objective measures from each shot versus vibration level rating, for each of the test rackets. For the subjective ratings of power, control and feel, racket averages of the objective measures were used and comparisons were again conducted for each racket and each stroke.

7.4.1 Forehand

The correlations between the individual's results were varied with no significant trend being observed. Several different objective measures were found to correlate positively with the perceived level of vibration for each racket. However, there were no clear trends between the rackets, with some correlating to knuckle RMS and SRMS measures (racket B) and others to racket RMS and SRMS measures (racket D). Therefore the overall results for all rackets were instead considered. Table 7.15 shows the correlations between each of the objective measures versus shot performance and vibration rating for all forehand shots. No correlations were found for the average objective measures and the subjective ratings of power, control and feel.

Table 7.15: Spearman correlation values for objective measures versus standardised vibration rating and shot performance for forehand shots

<table>
<thead>
<tr>
<th>Racket throat RMS</th>
<th>Shot performance</th>
<th>Vibration rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racket throat SRMS</td>
<td>-0.047</td>
<td>0.134 (^\dagger)</td>
</tr>
<tr>
<td>Racket throat MaxRMS</td>
<td>-0.046</td>
<td>0.089</td>
</tr>
<tr>
<td>Knuckle RMS</td>
<td>0.106</td>
<td>0.087</td>
</tr>
<tr>
<td>Knuckle SRMS</td>
<td>0.143 (^\dagger)</td>
<td>0.137 (^\dagger)</td>
</tr>
<tr>
<td>Knuckle MaxRMS</td>
<td>0.108 (^\dagger)</td>
<td>0.003</td>
</tr>
<tr>
<td>Racket throat damping ratio</td>
<td>0.169 (^\dagger)</td>
<td>0.000</td>
</tr>
<tr>
<td>Knuckle damping ratio</td>
<td>0.059</td>
<td>-0.109</td>
</tr>
<tr>
<td>x-axis impact location</td>
<td>-0.179 (^\dagger)</td>
<td>-0.012</td>
</tr>
<tr>
<td>y-axis impact location</td>
<td>-0.041</td>
<td>0.041</td>
</tr>
<tr>
<td>Standardised vibration rating</td>
<td>-0.190 (^\dagger)</td>
<td></td>
</tr>
</tbody>
</table>

\(^\dagger\) significant at 0.01 level
\(^\dagger\) significant at 0.05 level

Shot performance produced positive correlations with knuckle RMS and MAXRMS measures as well as racket throat damping ratios. Negative correlations were found between x-axis impact locations and standardised vibration ratings. Essentially, this meant that as the point of impact moved towards
the racket throat the level of vibration decreased. However, the Spearman correlation does not assume a linear relationship and therefore the shape of this trend is not determined. For the subjective vibration ratings, positive correlations were found with the racket throat RMS and MaxRMS measures, and knuckle SRMS measures.

7.4.2 Serve

Again the individual subject correlations varied largely, and results for all of the test rackets and serve shots are discussed. The correlations for each racket were found to produce varied correlations with no apparent trend. For all serve shots significant correlations were discovered for both the objective measures versus standardised vibration ratings and the mean objective measures correlated with the measures of power, feel and control, these results are separated into Tables 7.16 and 7.17.

Table 7.16: Spearman correlation values for objective measures versus standardised vibration rating and shot performance for serve shots

<table>
<thead>
<tr>
<th>Measure</th>
<th>Shot performance</th>
<th>Vibration rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racket throat RMS</td>
<td>-0.089</td>
<td>0.250†</td>
</tr>
<tr>
<td>Racket throat SRMS</td>
<td>-0.110</td>
<td>0.230†</td>
</tr>
<tr>
<td>Racket throat MaxRMS</td>
<td>-0.047</td>
<td>0.113</td>
</tr>
<tr>
<td>Knuckle RMS</td>
<td>-0.108</td>
<td>0.425†</td>
</tr>
<tr>
<td>Knuckle SRMS</td>
<td>-0.079</td>
<td>0.407†</td>
</tr>
<tr>
<td>Knuckle MaxRMS</td>
<td>-0.012</td>
<td>0.391†</td>
</tr>
<tr>
<td>Racket throat damping ratio</td>
<td>0.044</td>
<td>0.073</td>
</tr>
<tr>
<td>Knuckle damping ratio</td>
<td>0.000</td>
<td>-0.250†</td>
</tr>
<tr>
<td>x-axis impact location</td>
<td>0.101</td>
<td>-0.069</td>
</tr>
<tr>
<td>y-axis impact location</td>
<td>-0.058</td>
<td>0.035</td>
</tr>
<tr>
<td>Standardised vibration rating</td>
<td>-0.310†</td>
<td></td>
</tr>
</tbody>
</table>

† significant at 0.01 level

The serve results show correlation between the standardised subjective vibration rating and the measures of knuckle and racket RMS, SRMS, and knuckle MaxRMS. Significant correlation between shot performance and racket control rating was found. Negative correlations were observed between knuckle damping ratio, shot performance and vibration rating, and between the subjective rating of control and the mean measures of racket throat RMS and SRMS and knuckle SRMS and MaxRMS.

7.4.3 Volley

The individual correlations were again varied with no clear trends emerging. Very few correlations were found with the individual rackets, therefore only the correlations from all the volley shot results are reported. Like the forehand, there were no correlations between mean objective measures and subjective ratings of power, control and feel. The correlations between the objective values and standardised vibration measures is shown in Table 7.18.
Table 7.17: Spearman correlation values for mean objective measures versus subjective ratings for serve shots

<table>
<thead>
<tr>
<th>Objective measure</th>
<th>Power</th>
<th>Control</th>
<th>Feel</th>
<th>Standardised vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racket throat RMS</td>
<td>0.057</td>
<td>-0.385†</td>
<td>0.098</td>
<td>0.339†</td>
</tr>
<tr>
<td>Racket throat SRMS</td>
<td>-0.059</td>
<td>-0.351†</td>
<td>0.092</td>
<td>0.295†</td>
</tr>
<tr>
<td>Racket throat MaxRMS</td>
<td>-0.050</td>
<td>-0.174</td>
<td>0.028</td>
<td>0.165</td>
</tr>
<tr>
<td>Knuckle RMS</td>
<td>0.026</td>
<td>-0.258</td>
<td>-0.093</td>
<td>0.283</td>
</tr>
<tr>
<td>Knuckle SRMS</td>
<td>-0.043</td>
<td>-0.348†</td>
<td>0.045</td>
<td>0.442†</td>
</tr>
<tr>
<td>Knuckle MaxRMS</td>
<td>-0.075</td>
<td>-0.396†</td>
<td>0.030</td>
<td>0.506†</td>
</tr>
<tr>
<td>Racket throat damping ratio</td>
<td>0.197</td>
<td>-0.224</td>
<td>-0.084</td>
<td>0.050</td>
</tr>
<tr>
<td>Knuckle Damping ratio</td>
<td>-0.054</td>
<td>0.215</td>
<td>0.052</td>
<td>-0.298</td>
</tr>
<tr>
<td>Shot performance</td>
<td>0.253</td>
<td>0.532†</td>
<td>-0.174</td>
<td>-0.397‡</td>
</tr>
</tbody>
</table>

† significant at 0.01 level
‡ significant at 0.05 level

The results in Table 7.18 show similar results to the serve. Positive correlations were again found between racket throat and knuckle RMS, SRMS, and MaxRMS measures and the standardised rating of vibration as well as correlation with the x-axis impact location. Negative correlations were found between the knuckle damping ratio and perceived level of vibration.
Table 7.18: Spearman correlation values for objective measures versus standardised vibration rating and shot performance for volley shots

<table>
<thead>
<tr>
<th></th>
<th>Shot performance</th>
<th>Vibration rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racket throat RMS</td>
<td>-0.099</td>
<td>0.207†</td>
</tr>
<tr>
<td>Racket throat SRMS</td>
<td>-0.092</td>
<td>0.204†</td>
</tr>
<tr>
<td>Racket throat MaxRMS</td>
<td>-0.053</td>
<td>0.129</td>
</tr>
<tr>
<td>Knuckle RMS</td>
<td>-0.116</td>
<td>0.262†</td>
</tr>
<tr>
<td>Knuckle SRMS</td>
<td>-0.109</td>
<td>0.260†</td>
</tr>
<tr>
<td>Knuckle MaxRMS</td>
<td>-0.073</td>
<td>0.285†</td>
</tr>
<tr>
<td>Racket throat damping ratio</td>
<td>-0.050</td>
<td>0.095</td>
</tr>
<tr>
<td>Knuckle damping ratio</td>
<td>-0.006</td>
<td>-0.192†</td>
</tr>
<tr>
<td>x-axis impact location</td>
<td>-0.012</td>
<td>0.141†</td>
</tr>
<tr>
<td>y-axis impact location</td>
<td>0.003</td>
<td>-0.109</td>
</tr>
<tr>
<td>Standardised vibration rating</td>
<td>-0.157†</td>
<td></td>
</tr>
</tbody>
</table>

† significant at 0.01 level
‡ significant at 0.05 level
7.5 Effect of impact location

The effect of impact location on both the measured vibration and the vibration perceived by the subject was investigated and results provided in this section.

Table 7.19: Spearman correlation values for objective measures versus x and y impact locations for each stroke type

<table>
<thead>
<tr>
<th>Measures</th>
<th>Forehand</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x-axis</td>
<td>y-axis</td>
<td>x-axis</td>
<td>y-axis</td>
<td>x-axis</td>
<td>y-axis</td>
</tr>
<tr>
<td>Racket throat RMS</td>
<td>0.343 †</td>
<td>0.171 †</td>
<td>0.125</td>
<td>0.239 †</td>
<td>0.661 †</td>
<td>-0.084</td>
</tr>
<tr>
<td>Racket throat SRMS</td>
<td>0.366 †</td>
<td>0.172 †</td>
<td>0.179 †</td>
<td>0.179 †</td>
<td>0.663 †</td>
<td>-0.088</td>
</tr>
<tr>
<td>Racket throat MaxRMS</td>
<td>0.501 †</td>
<td>0.199 †</td>
<td>0.416 †</td>
<td>0.179 †</td>
<td>0.485 †</td>
<td>-0.084</td>
</tr>
<tr>
<td>Knuckle RMS</td>
<td>0.129 †</td>
<td>0.237 †</td>
<td>-0.213 †</td>
<td>-0.038</td>
<td>0.593 †</td>
<td>-0.007</td>
</tr>
<tr>
<td>Knuckle SRMS</td>
<td>-0.264 †</td>
<td>0.103</td>
<td>-0.180 †</td>
<td>-0.029</td>
<td>0.590 †</td>
<td>-0.004</td>
</tr>
<tr>
<td>Knuckle MaxRMS</td>
<td>0.295 †</td>
<td>0.263 †</td>
<td>-0.044</td>
<td>0.019</td>
<td>0.432 †</td>
<td>0.010</td>
</tr>
<tr>
<td>Racket throat damping ratio</td>
<td>-0.084</td>
<td>-0.023</td>
<td>-0.033</td>
<td>-0.017</td>
<td>0.320 †</td>
<td>-0.047</td>
</tr>
<tr>
<td>Knuckle damping ratio</td>
<td>-0.007</td>
<td>0.047</td>
<td>-0.182 †</td>
<td>0.024</td>
<td>-0.185 †</td>
<td>-0.121 †</td>
</tr>
<tr>
<td>Standardised vibration rating</td>
<td>-0.012</td>
<td>0.041</td>
<td>-0.069</td>
<td>0.035</td>
<td>0.141 †</td>
<td>-0.109</td>
</tr>
<tr>
<td>Shot performance</td>
<td>-0.179 †</td>
<td>-0.041</td>
<td>0.101</td>
<td>-0.058</td>
<td>-0.012</td>
<td>0.003</td>
</tr>
</tbody>
</table>

† significant at 0.01 level
‡ significant at 0.05 level

The impact location correlations in Table 7.19 highlight some of the differences between the shots. The forehand results show correlations between both the x and y axis impact locations and the various rms measures. The serve results demonstrate that this stroke is not as influenced by impact location as the other two strokes. The volley results show a large number of correlations for the x-axis measures compared to only one on the y-axis. The volley is the only stroke where a correlation between impact location and perceived vibration rating was found. Impact locations were plotted versus the subjective ratings of impact and objective measures such as racket throat or knuckle measures of rms, Figure 7.8 shows a comparison between the impact locations and standardised subjective rating for each stroke.

Variances in the responses of the individual subjects make clear distinction of preferred regions producing lowest levels of vibration difficult, but it can be seen that players generally perceived lower levels of vibration with central impacts. Impacts deviating from the long axis of the racket frame demonstrate an increase in the perceived level of vibration. The forehand also demonstrates an increase in the perceived level of vibration as the impact location approaches the throat of the racket, this is not as apparent for the other two strokes, possibly due to lack of test impacts at these locations.

The effect of impact was also compared versus the rms measures. The measures of MaxRMS are shown as these produced the best correlations with impact location. The results of these are shown in Figures 7.9 to 7.10. Trends can be observed. The first is that as each Figure uses the same colour intensity scale to represent the rms values for each stroke, it is clearly visible that the forehand stroke
produces the lowest MaxRMS values across the string bed. The second trend demonstrates that for the racket measures (Figure 7.9) an area of lower vibration appears to be situated between the 5–9 point of the x-axis. It can also be observed from the serve and volley charts that an increase in measured MaxRMS occurs as the impact locations approach the throat and horizontal edge of the stringbed. On the knuckle measures chart (Figure 7.10) the area of low vibration appears to have spread along the string bed, suggesting that the damping of the hand attenuates some of the effects.

These results have illustrated some of the effects of impact location. The variability in the results is likely caused by comparing different rackets results altogether. To improve these results, the effect of impact location on the rms measures and standardised vibration rating was examined for each racket.
Figure 7.8: Plots of impact location versus standardised vibration rating
Figure 7.9: Plots of impact location versus racket throat MaxRMS measures
Figure 7.10: Plots of impact location versus knuckle MaxRMS measures
7.5.1 Forehand

The first of the strokes investigated was the forehand. Due to the small number of impacts conducted for each subject and racket, the effect of impact location was difficult to determine. A considerable spread of impact locations and values was required to enable comparisons to be drawn. The effect of impact location on each racket was therefore examined for each stroke. Mean values for the vibration rating, and MAX RMS were measured for a $3 \times 3$ string area using both the mean impact location of the stroke or the mean impact location of the racket as the centrepoint. Figure 7.11 shows an example of the two measurement areas. This analysis was conducted to remove the effect of the varied dispersion of impact location values on the overall mean values reported for each racket, allowing the results for a known area of the racket to be compared. The population mean (PM) refers to the area around the mean impact location of the specific stroke investigated, whereas the sample mean (SM) investigates the area around the mean impact location of the specific racket/individual. The two measures provide a comparison between the same area with each racket and the area of the preferred impact location.

![Figure 7.11: Comparison of two impact areas](image)

Due to small differences between the overall shot and racket mean impact locations the results of both sample and population mean were very similar. The results of the sample mean are plotted in Figure 7.12. For the forehand the only difference was the higher vibration ratings for the central locations for racket F compared to the other test rackets. The impact locations for each racket are shown in Figure 7.13, where the variation between rackets can be observed.
Figure 7.12: Comparison of SM measures for each stroke
Figure 7.13: Comparison of forehand racket vibration rating for each test racket
7.5.2 Serve

Figures 7.14 show the comparison of each racket standardised vibration rating and impact location for the serve stroke. The area measures for this stroke (Figure 7.12) show several trends. Racket E clearly rated lower than several of the test rackets for central impacts. For the MAXRMS measures, racket B is again much higher than the novel rackets and F is the highest for knuckle measures.

![Comparison of serve racket vibration rating for each test racket](image)

Figure 7.14: Comparison of serve racket vibration rating for each test racket

Standardised vibration ratings varied, which is again is likely due to individual preferences for impact location and sensations they experience. This produces varied results when comparing the overall racket results for each subject.
7.5.3 Volley

Figures 7.15 show the comparison of each racket's vibration measures the volley stroke. The area measures (Figure 7.12) did not show as many clear trends as the serve, but racket B again produced the highest MAXRMS measures for central impacts.

Figure 7.15: Comparison of volley racket vibration rating for each test racket
7.6 Frequency content

The final analysis investigated the frequency content of the vibration data. The vibration data was converted into the frequency domain and trends in the frequency content of each shot were investigated to determine how frequency becomes responsible for certain impact sensations.

![Figure 7.16: Frequency weighting functions](image)

As the response of humans to vibration is not linear, frequency weightings are used to adjust the frequency spectra accordingly to represent the contributions of various frequencies. Figure 7.16 shows the three weighting functions considered for these results. ISO5349 is the recognised standard for assessment of vibration transmitted to hands by tools. Equal sensation and threshold weighting functions were selected from Reynolds et al. (1977b). This study was selected as it was conducted using a hand gripping a cylindrical rod with grip force values similar to those reported by Hatze (1992) for forehand grip pressure in tennis. A method to frequency weight the spectra using a filter was incorporated in ISO5349. However, no such methodology existed for the Reynolds et al. (1977b) curves. Only the Reynolds et al. (1977b) threshold curves were converted, as the equal-sensation curves are almost identical to those of ISO5348. The threshold curves were converted by first inverting the data from Figure 5.3 and standardising the curve data, therefore the most sensitive frequencies would be given a value of 1 and the remainder of the frequencies would be attenuated accordingly. Two polynomial curves, one for the frequency range 0 to 315 Hz and another for 315 to 1000 Hz were used to define the Human Sensitivity (HIS) frequency weighting curve. The polynomial coefficients of these curves are shown in Table 7.20.

The Reynolds et al. (1977b) threshold curve was preferred for the weighting function as the ISO5349 weighting function severely attenuated frequencies above 50 Hz, the frequencies linked with causing actual physical damage to humans. Frequencies below 50 Hz in tennis are usually associated with the movement of the racket. Modal analysis of the racket frames and previous studies (Brody, 1981;
Table 7.20: Polynomial curves for Human Sensitivity weighting

<table>
<thead>
<tr>
<th>Frequency, $f$ (Hz)</th>
<th>$f^4$</th>
<th>$f^3$</th>
<th>$f^2$</th>
<th>$f^1$</th>
<th>$f^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; f \leq 315$</td>
<td>$6.6\times10^{-10}$</td>
<td>$-5.7\times10^{-7}$</td>
<td>$1.4 \times10^{-4}$</td>
<td>$-0.0059$</td>
<td>$0.024$</td>
</tr>
<tr>
<td>$315 \geq f \leq 1000$</td>
<td>$0$</td>
<td>$0.048$</td>
<td>$0.09$</td>
<td>$-0.051$</td>
<td>$0.035$</td>
</tr>
<tr>
<td>$f &gt; 1000$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

Fyson, 1998; Mohanty & Rixen, 2002) have all found the first mode of a tennis racket to be between 80–200 Hz, depending on construction and shape. Griffin (1990) also found that humans are most sensitive to vibration at frequencies of approximately 250 Hz.

Figures 7.17 to 7.22 show a comparison of the unweighted traces of racket and knuckle vibration respectively, for each racket and each stroke allowing a comparison of the effects of the the stroke type on the vibration frequencies experienced. The coloured traces for each chart show the average spectra from each test subject and the black line represents the mean spectra for the test racket. A consistent trend with the peaks of the frequency spectra can be observed for each racket. Variation in the magnitude of each of the spectra can be observed due to variations in individual produced levels of impact vibration.

The HS weighting was applied to the knuckle traces, as the weightings were not considered relevant for racket measures, as expected similar trends between the subject traces were shown.

The results were analysed by stroke type, with comparisons between the strokes being investigated later in this section. For each figure peaks in the data between 0–40 Hz can be observed, these frequency peaks are generally ignored as they are considered to be caused by the movement of the implement.

Comparison of the rackets for each stroke was conducted, Figures 7.23 and 7.24 demonstrate the average frequency spectra for both measures from each racket and the weighted knuckle measures, respectively.

7.6.1 Forehand

From examination of the racket frequency measures, it can be observed that the first noticeable peak is found around 120 Hz for racket B and at a lower frequency range of 80–100 Hz for the novel handled rackets (C–F). A considerable variation between the magnitudes of the first peak for each subject and racket used was observed, however in general the magnitude of the first peak is less than that of the second noticeable peak for all of the rackets. Noticeable racket differences begin to emerge at the second major frequency peak. Racket B (standard racket) typically demonstrates its second major peak at around 340 Hz, but the second peaks for the novel handled rackets are found at around 230 Hz. As mentioned the magnitudes of these peaks vary between subjects and rackets but both the
Figure 7.17: Racket B and C measures of racket unweighted frequency spectra, coloured lines represent test subjects average results and black line represent overall racket mean spectra
Figure 7.18: Racket D and E measures of racket unweighted frequency spectra, coloured lines represent test subjects average results and black line represent overall racket mean spectra.
Figure 7.19: Racket F measures of racket unweighted frequency spectra, coloured lines represent test subjects average results and black line represent overall racket mean spectra.
Figure 7.20: Racket B and C measures of knuckle unweighted frequency spectra, coloured lines represent test subjects average results and black line represent overall racket mean spectra
Figure 7.21: Racket D and E measures of knuckle unweighted frequency spectra, coloured lines represent test subjects average results and black line represent overall racket mean spectra.
Figure 7.22: Racket F measures of knuckle unweighted frequency spectra, coloured lines represent test subjects average results and black line represent overall racket mean spectra
Figure 7.23: Comparison of racket results for unweighted racket and knuckle frequency spectra
Figure 7.24: Comparison of racket results for weighted knuckle measures of frequency spectra
peaks of racket B and the novel handled rackets are larger than the magnitude of the first peaks. Relatively small (≤ 10 g\text{rms}) peaks can also be found at around 600–620 Hz for all rackets. Observable peaks at approximately 1000 Hz can also be found. Examining the knuckle frequency measures, the magnitudes of the frequencies demonstrate a different pattern to those of the racket measures. The first spectra peak is similar for each of the rackets tested, again around 100–120 Hz. The magnitudes of the racket B’s first peaks are generally larger than those of the second peak. For the novel handled rackets, rackets C and D demonstrate larger second peak magnitudes than first peaks and rackets E and F show a split between some subjects experiencing impacts with larger second peaks and others with larger first peaks. The trends of the second peaks for each of the rackets is consistent with that of the racket measures. Racket B is of generally higher frequency at approximately 340 Hz and the novel racket measures being approximately 220–240 Hz. Again the third frequency peaks were shown at around 600–640 Hz, although racket F demonstrated peaks at a higher frequency of around 730 Hz. Rackets D and E also demonstrated some peaks at around 370 Hz which were not observable with the other novel handled rackets.

The force imparted on the ball at impact or post-impact, ball speed was not measured. It is not possible to speculate on the force of the impacts with each racket and it is difficult to make magnitude comparison from the mean racket frequency spectra. However, work by Knudson & Blackwell (2005) suggest that the impact kinematics of successful forehands for advanced subjects are highly consistent, given similar ball inbound characteristics and identical shot type. By statistically comparing the results of every shot, the effect of a small number of abnormal impacts can be negated. This approach is supported by the lack of significant differences between the racket impact locations and shot performance for all shots given that the impact kinematics are relatively similar over the entire sample. Non-parametric Mann-Whitney tests were used to investigate significant differences between the magnitudes of the frequency peaks. There were no observable differences between the test rackets in the 40–150 Hz range. At 180–280 Hz and 280–380 Hz significant differences (p < 0.05) were discovered between racket B and the novel handled rackets for both racket and knuckle measures. Racket B was significantly lower magnitude in the 180–280 Hz region and significantly higher magnitude in the 280–380 Hz region.

Racket B was also found to be significantly larger in the frequency range 550–650 Hz than rackets C and F (U=134.5, r=-0.25; U=948, r=-0.36) respectively for racket measures, but only between rackets B and F for the knuckle measures (U=1230, r=-0.22). Racket D possessed significantly larger values than racket F in both the 280–380 and 550–650 Hz region for racket measures (U=961, r=-0.39 and U=1201, r=-0.27 respectively) but was only significantly larger than racket F in the 550–650 Hz region for the knuckle measures (U=1136, r=-0.30).
To investigate the effect of the frequency peaks on subjective perceptions, the frequency traces were arranged into four frequency ranges, each range corresponding to frequencies of observable peaks in the spectra measures, the four frequency ranges are:

- **Range 1** = 40–150 Hz
- **Range 2** = 180–280 Hz
- **Range 3** = 280–380 Hz
- **Range 4** = 550–650 Hz

The magnitude values of each peak within each frequency range were calculated and correlated against the standardised subjective vibration rating. The results in Table 7.21 show the Spearman correlation coefficients for all test rackets for the forehand stroke.

<table>
<thead>
<tr>
<th>Racket frequency ranges</th>
<th>Knuckle frequency ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Vibration rating</td>
<td>0.211†</td>
</tr>
</tbody>
</table>

† significant at 0.01 level  
‡ significant at 0.05 level

The correlations in the table show that the standardised vibration ratings correlate positively with both racket and knuckle first and third frequency ranges.

### 7.6.2 Serve

The first peaks of the racket measures in the spectra were at approximately at 100–115 Hz for racket B and slightly lower frequencies of 80–100 Hz for the novel rackets. Comparing the magnitudes of each racket’s first peak with second peak it could again be seen rackets B, C and E had second peaks with larger magnitude than the first peak. This was not the case for racket D and the majority of subjects using racket F in which the first peak was of greater magnitude. The second peaks in the spectra were again approximately 310–340 Hz for racket B and of lower frequency (200–240 Hz) for the novel handled rackets. Peaks at around 600-640 Hz and 1000 Hz were again noticeable. For the knuckle measures, the first peaks again occurred at approximately 110 Hz for racket B and at slightly lower frequencies for the novel handled rackets. The magnitudes of the first peaks relative to the second peaks showed that rackets C, E, and F exhibited larger second peak magnitudes than 1st peaks, but this trend was not observed with rackets D and B which had larger first peak magnitudes. The peak,
for racket B, at approximately 350 Hz remained with no observable peaks for the novel rackets in this region. There were no peaks observed at frequencies above 500 Hz.

Correlations between the frequency ranges and impact locations and standardised vibration ratings were again conducted, the results are shown in Table 7.22.

Table 7.22: Spearman correlation values for impact location and standardised vibration rating versus magnitudes of racket and knuckle frequency ranges for serve strokes

<table>
<thead>
<tr>
<th>Racket frequency ranges</th>
<th>Knuckle frequency ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Vibration rating</td>
<td>0.286†</td>
</tr>
</tbody>
</table>

† significant at 0.01 level

Correlations between the standardised vibration ratings and frequency range magnitudes of the first frequency range with the racket and every frequency range of the knuckle measures are shown.

Using Mann-Whitney measures to investigate the magnitudes of the frequency peaks, all of the novel rackets were shown to be significantly \( p < 0.01 \) lower in magnitude in the 280–380 Hz frequency range than those of racket B. However, these significant differences are only observable between racket E and racket B \( (U=396, r=-0.30) \) for knuckle measures. In the 40–150 Hz range, all of the rackets possessed similar racket frequency magnitudes, except for racket E, which is of significantly lower magnitude than the other rackets. In the 180–280 Hz region, the frequency peaks of rackets C and F were significantly higher in magnitude than those of rackets B, D and F for racket measures. For the knuckle, all of the novel rackets were found to be of significantly higher magnitude than racket B, but there were no significant differences between each of the novel rackets in this frequency range. In the 550–650 Hz region, racket F was found to be of significantly lower magnitude than rackets B, C and D, but the knuckle measures showed that all rackets were of significantly higher magnitude than racket B \( (U=397, r=-0.30) \).

7.6.3 Volley

The first frequency peaks are similar to those of the previous two shots. The magnitudes of the first peaks showed that the novel rackets all possessed lower magnitude first peaks compared to the second peaks, however for racket B the majority of the peaks of the 1st spectra were larger than those of the second peaks. Similar trends to the previous strokes for the second frequency peaks were again observed. Peaks were also noticeable at 580–630 Hz and at approximately 1000 Hz. For the knuckle measures, similar trends to those of the previous two strokes were also shown, however the magnitudes of the first frequency peak for the novel rackets were unanimously lower in magnitude than the second frequency peaks. Racket B, again exhibited a peak in frequency at approximately 340 Hz. The volley knuckle measurements demonstrated a peak at around 1000 Hz.
Examining the correlations between the magnitudes of the frequency regions and the x and y-axis impact locations and standardised vibration rating, the results are shown in Table 7.23.

Table 7.23: Spearman correlation values for impact location and standardised vibration rating versus magnitudes of racket and knuckle frequency ranges for volley strokes

<table>
<thead>
<tr>
<th>Racket frequency ranges</th>
<th>Knuckle frequency ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration rating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.209* 0.222* -0.040 0.111</td>
</tr>
</tbody>
</table>

* significant at 0.01 level

For the vibration ratings, like the other two strokes, the effect of the first frequency region correlates with the perceived level of vibration. However, unlike the serve and forehand volley there is no correlation between the magnitudes of the frequency peaks in the third frequency region and the perceived level of vibration. The effect of the second frequency region does correlate for both racket and knuckle measures as well as the fourth frequency region for the knuckle measures.

Comparing the frequency peaks using Mann-Whitney test for the racket and knuckle measures. No significant differences were found between either measures for the rackets in the 40-150 Hz frequency range. In the 180-280 Hz frequency range significant differences emerge. For the racket measures, racket B was found to be of significantly (p < 0.01) lower magnitude than all of the the novel handled rackets, except for racket D. Racket C was found to be significantly higher than the rest of the test rackets. Racket B was observed to also be significantly lower for the knuckle measures versus all of the novel handled rackets, with racket C again the largest magnitude of all the test rackets. For the frequency range 280-380 Hz, racket B was found to be of significantly greater magnitude than all of the novel handled rackets for both racket and knuckle measures.

Stroke comparison

Figures 7.25 and 7.26 show a comparison of the frequency spectra for each shot type, with each of the test rackets. Racket variations in the frequency results can be observed.

Examining the variations between the different strokes for racket B, the standard racket. It can be seen that there is a significant difference between the racket peak magnitudes in the 40-150 Hz frequency range between the forehand and the serve (U=623, p < 0.01, r=-0.35), but no significant differences between the forehand and volley and serve in this range. In the 180-280 Hz range there are several noticeable differences. For the knuckle measures, significant differences exist between the magnitudes of each of the strokes, with the volley producing the highest magnitude followed by the serve. For the racket measures the volley is significantly higher than the forehand and serve,(U=809, r=-0.45) and (U=718, r=-0.20) respectively. There are no significant difference between the magnitudes of the forehand and serve. In the 280-380 Hz region all strokes were found
Figure 7.25: Comparison of racket measures for three stroke types of unweighted frequency spectra.
Figure 7.26: Comparison of knuckle measures for three stroke types of unweighted frequency spectra
to produce similar magnitude peaks for each stroke, the volley stroke produced significantly higher magnitudes than the forehand and the serve for knuckle measures, \( U=770, r=-0.23 \), \( U=334, r=-0.50 \) respectively. In the 550–650 Hz region the knuckle measures for the serve were found to be significantly lower than those of the forehand and volley, \( U=770, r=-0.23 \) and \( U=653, r=-0.25 \) respectively, with no significant differences between the forehand and volley.

Examining the novel handled rackets. In the 40–150 Hz region, both rackets C and D demonstrate significantly \( p < 0.05 \) larger frequency peaks for the serve versus the forehand for racket and the knuckle measures. For racket C, the volley is found to have significantly higher magnitude than the forehand \( U=838, r=-0.27 \) for racket measures, but this is only found for the knuckle measures with racket D \( U=1290.5, r=-0.31 \). For rackets E and F racket measures showed that there were significantly larger serve magnitudes versus the forehand for racket measures. Both rackets also demonstrated significantly larger volley than forehand measures \( U=1251, r=-0.25 \) and \( U=970, r=-0.23 \) respectively, with these trends observed for both measures with racket F.

In the 180–280 and 280–380 Hz frequency ranges, a clear trend amongst all of the rackets could be observed. The volley had a significantly higher magnitude peak, for both racket and knuckle measures, than the forehand with both frequency ranges. The volley was also significantly larger than the serve peak magnitudes for knuckle measures, but only with racket measures for rackets D and F. No significant differences were found between the knuckle measures between the forehand and serve. The racket measures found significant differences between racket measures in the 280-380 Hz frequencies for rackets C and E \( U=602, r=-0.37 \) and \( U=720, r=-0.29 \) respectively. At the highest frequency range examined, 550–650 Hz, the knuckle measures were generally found to be of significantly higher magnitude for the forehand to the serve, except racket F in which the serve magnitudes were significantly higher than those of the forehand \( U=641, r=-0.27 \). The serve was also significantly lower than the volley for knuckle measures of rackets C, D and E in this region. Rackets C, E and F exhibited significant differences for knuckle measures between the higher magnitudes of the volley and the those of the forehand frequency peaks \( U=926, r=-0.21 \), \( U=1330, r=-0.21 \) and \( U=639, r=-0.44 \) respectively.

The frequency spectra were also compared with various impact locations to determine the effect of impact location on the frequency content of the ensuing vibration. Subjects that provided multiple identical impacts at a couple of locations on the string bed were easiest to analyse. The forehand and volley provided most shots per racket for comparison, but, the volley was the easiest stroke for trends to be observed. No clear trends were observable for the forehand. Results for racket B can be seen in Figures 7.27 for racket measures, as the impact location trends were easiest to establish with these measures.
Figure 7.27: Racket B racket frequency spectra, comparison of results for impact location
The effect of the movement of impact location along the \(x\)-axis produces a noticeable effect on the frequency spectra. The trend is clearest with the racket measures, but similar trends can be seen with the knuckle measures. Impact locations around 9 or 10 on the \(x\)-axis, specific position depending on the subject and the impact locations available for comparison, show that there is little or no frequency peak at 150 Hz, however for impacts at \(x\)-axis location higher or lower than these values a large peak can be found at about the 150 Hz region. This suggests the presence of a racket node around the 9 or 10 region of the stringbed when gripped. Impacts away from the longitudinal centre line (\(y\)-axis) appear to produce minimal effect on the measured vibration and vibration spectra for racket B. Similar trends were observed with the novel handled rackets. An example is shown in Figure 7.28. Although, observations of the trends could be made with most subjects, those producing the most consistent impact locations were selected for comparison as they provide best illustration of the trends.
For the novel handled rackets, deviations along the $y$-axis also appear to produce increased content in the frequency peaks at approximately 350 Hz. Although all rackets appear to produce some frequency content in this frequency range, the impacts away from the centre point increase the magnitude of this frequency peak. Similar trends were observed with the serve stroke for all rackets, although they were much harder to discern with the knuckle measures from the novel handed rackets than they were for the volley.
7.7 Summary of vibration results

The testing of the handle concepts incorporated several different measures and methods of analysing the vibration results, therefore prior to the discussion of the results a brief summary of the key vibration trends observed is included:

- Significant differences in vibration measures for each racket existed between the subjects.
- The rate of vibration damping measured at the knuckle was found not to be influenced by racket type, however significant differences existed between subject measures.
- For racket measures of damping ratio significant differences were found between the rackets. Racket C was found to produce significantly higher damping values than several of the test rackets for all of the strokes.
- For all strokes, correlations between the perceived level of vibration and knuckle measures of SRMS were found.
- Correlations between impacts along the $x$-axis and the perceived level of vibration were much more common than correlations with impacts along the $y$-axis.
- Investigations into the vibration magnitudes for each impact location showed that impacts around the 6–9 point on the $x$-axis generally produced the lowest vibration magnitudes.
- Racket B produced the highest racket throat rms measures, but for knuckle measures produced values similar to or lower than the other test rackets.
- For each stroke, correlations between the perceived level of vibration and the magnitude of the peak of the first frequency range, for both racket and knuckle measures, were found.
- The effect of impact location on the first mode of vibration was observed in the frequency spectra. A reduction in the frequency content around 150 Hz could be observed with impacts occurring close to the predicted nodal points (between 6–10 along the $x$-axis).

The discussion explains the significance of these results to the handle design and compares them with results of previous studies.
Analysis of novel handle concept: Discussion of results

The investigation of various racket strokes in simulated play situations generates numerous issues for data collection and interpretation that need be resolved. Traditionally, laboratory based tests have been used to control these variabilities (Elliott et al., 1980; Hennig et al., 1992; Li et al., 2004; Maeda & Okauchi, 2002; Stroede et al., 1999). However, by constraining the movement of the racket and minimising deviations in impact locations, the ability to interpret subject differences is lost. Thus, in order to develop an understanding of how rackets behave and players respond to this behaviour investigations using simulated play conditions must be refined.

8.0.1 Overview of testing

Clear differences were observed between the three racket strokes. The volley produced significantly different impact locations from both the serve and forehand strokes, though there were no significant differences between the serve and forehand impact locations. Results also showed significant differences between the impact locations for individual subjects with each stroke type. The volley produced the highest number of significantly different subject impact locations, with the forehand producing the least number of significantly different impact locations between subjects. A larger proportion of the significant differences were found for the y-axis impact locations. Individual coefficient of variance values are typically found to be below 0.25 for both x and y axis measures, with the x-axis impact locations typically having higher coefficient of variance than the y-axis measures for each subject, it is possible to conclude that subjects may try to control impact along the y-axis more than they would impacts along the x-axis. There were few significant differences between impact locations for rackets used by individual subjects or between the rackets overall. This indicates that the specific racket-type is not responsible for deviation of impact location produced by the subject. However, the use of different racket frame geometries/constructions would need to be investigated to validate this.

It is likely that subject technique and preference of impact sensation is responsible for the variations in
impact location. The use of generalised stroke arrangements or investigations into racket performance should be based on a specific stroke, due to the clear differences in stroke mechanics and technique. The effect of the varying impact locations for specific strokes and inter-subject variability of the impact conditions could result in differing perceptions of impact sensations, based on the shot type or racket used. It is likely that these variations are responsible for the wide variety of tennis rackets available, since players select racket constructions which suit their stroke mechanics and subjective preferences.

8.0.2 Effect of impact location

The impact location, had a noticeable effect on the levels of vibration experienced by each subject. The x-axis measurements produced the most correlations with rms measures. Of all the strokes, the serve produced the least correlation between rms measures and impact location while the volley produced the most correlations. All the rms measures correlated with the x-axis, but not y-axis impact locations. In addition the volley was the only stroke that showed a correlation between impact location and subjective vibration rating. The forehand was the most influenced by y-axis deviations, with correlations between these measures and both racket and knuckle RMS measures, and knuckle MAXRMS measures. One problem identified with correlating measures of vibration to impact location is the effect of nodal points on the vibration measures. Correlations suggest that as the impact location increases in magnitude, the level of the vibration measure would also increase. This does not consider that across a particular axis length the impact location may encounter a node point. At this node point, corresponding mode frequencies of the vibration will reduce significantly, typically producing a reduction in the overall vibration magnitude. Once the impact location continues beyond a nodal point the modal frequency amplitude will increase again and therefore the overall vibration magnitude will increase.

As previously discussed, the relationship between the impact location and level of vibration has been shown not to be linear and is more likely to be modelled by a curve with a deflection corresponding to the node of the fundamental racket mode (Brody et al., 2002). Figure 8.1 plots the racket measures of SRMS for the standard racket (racket B) versus the x-axis impact co-ordinate. A 6th degree polynomial was found to produce the best fit through the data ($R^2=0.39$) and can be seen to produce similar trends to those curves produced by Brody et al. (2002), however due to a lack of impacts close to the tip and throat the curve is found to produce troughs at these regions, whereas a peak in vibration magnitude would be more expected if impacts were available in these areas. Similar trends were discovered with each of the test rackets and for each shot type.

The string bed of a tennis racket is purported to have between 2–3 sweetspots. Cross (1998); Mohanty & Rixen (2002) and Brody (1981) define the first sweetspot as the point of minimal initial shock, also known as the centre of percussion (COP). The second point is the vibration node, the
point at which minimal vibration for the fundamental mode of the racket is produced. The third point is defined by Brody (1981) and Mohanty & Rixen (2002) as the point of maximum coefficient of restitution, where the ball rebounds with most preserved energy. Figure 8.2 shows approximate locations of these points on a string bed.

The close proximity of the COP and the node location of the fundamental mode could be responsible for producing the large area of lower perceived vibration in the centre of the string bed for each stroke, seen in Figure 7.8. The results suggest that players are not solely influenced by the vibration experienced, and impacts at the COP may produce low perceived levels of vibration due to a reduction in the shock experienced by the subject’s arm. The presence of the node location can be observed on the racket MaxRMS measures, shown in Figure 7.9. The position of the node is inside the darker region around the 7–9 area of the x-axis. Studies have shown that the node point is not a straight line across the string bed (Brody et al., 2002), but a series of points which form an arc across the string bed (Figure 8.3).

The effect of the node positions are clearly demonstrated by Figures 7.27 to 7.28 comparing the effect of impact location on the frequency spectra. The position of the fundamental node was approximately the 9th string position along the x-axis, although deviations from this value may be caused by the varied impact locations along the y-axis due to the curved nature of the nodal line or differences in the exact position of the racket node. Experimental modal analysis found that the approximate frequencies of the first mode were around 120 Hz, indicating the likelihood of the x-axis influencing the first bending mode. The mode shapes from Appendix D demonstrate that it is possible for the node to located around the 9th string.

The node location may be responsible for some of the subjective differences in impact location, as each individual’s own racket may possess differing modal characteristics due to different node
Figure 8.2: The location of three racket sweetspots and dead spot area, adapted from Cross (1998)

Figure 8.3: The curved nature of racket nodal points (Brody et al., 2002)
positions. This may condition individuals to consistently impact the ball at locations similar to the node location of their own racket. Some subjects may also prefer to experience more vibration from the first mode than other subjects and therefore these subjects habitually impact the racket at impact locations reflecting this trend. Since the rackets used in the test protocol were of identical frame construction, no significant differences were discovered between impact locations for all rackets, even though they existed for the impact locations between subjects. It is difficult to speculate whether the use of varying racket geometries or constructions would have produced significant differences in impact location. Players may alter their position of impact to find the impact location producing the most preferable sensations for themselves.

8.0.3 Racket evaluation

The effect of the novel handle concept was found to significantly reduce the racket throat rms measures for many of the shot types versus the standard racket (B). However, this reduction did not yield a reduction of knuckle vibration. For the forehand stroke, racket C was found to be significantly greater than racket F for RMS and MaxRMS measures and significantly greater than racket B for RMS and SRMS measures. For the serve, racket B's results were significantly smaller in magnitude than all of the novel handled rackets for RMS measures. For the MaxRMS and SRMS measures, only racket F was significantly greater in magnitude than racket E. Examining the volley, rackets B and D were significantly lower in magnitude for all rms measures than the other novel handled rackets. These results suggest that characteristics of strokes are more suited toward specific construction rackets. The decreased knuckle RMS for racket B relative to all other rackets is likely due to the increased stiffness of the standard racket, allowing the vibration to be damped much quicker by the racket frame, as these account for the whole vibration trace. However, racket F composed of the least stiff springs had the highest rms measures for the serve and volley strokes, and also produced significantly lower MaxRMS and RMS measures for the forehand compared to racket C. Further vibration comparisons were also made with subjective ratings. Examining the forehand and serve vibration ratings (which satisfy the Kendall coefficient of concordance) racket C had the lowest perceived vibration rating for the forehand, but produced rms measures significantly higher than those of rackets B and F. However for the serve, the rms measures suggest that racket F produced significantly greater values than racket E. The vibration ratings show that overall, racket F produced the second highest vibration ratings and that racket E produced the lowest vibration ratings. However the large standard deviations of the vibration ratings make it difficult to determine the precise order that subjects rated the rackets.

Although there was considerable inter-subject variability in the magnitudes of the frequency spectra, there were apparent trends in the spectra shape for each of the rackets used. The first fundamental node of the racket vibration occurred at approximately 100–150 Hz. Modal analysis results indicated
that the novel handled rackets were generally of lower frequency. In addition, the magnitude of the first mode frequency peaks were of lower magnitude than those of the second lateral mode for the racket measures. Examination of the mode shapes suggested that the measurement at the racket throat was close to a node point for the first mode and very close to an anti-node point for the second mode. In general, all of the racket's first fundamental peaks were of lower frequency than the corresponding modal analysis measures. This is likely due to the effect of additional mass to the racket caused by the hand gripping at the handle. A noticeable discrepancy between the standard and novel handled rackets was observed for the position of the respective second peaks in the frequency spectra. The peaks for the novel handled rackets occurred at approximately 230 Hz, similar frequencies to the second bending modes discovered with modal analysis. However, the second peak for the standard racket is typically found at frequencies around 330 Hz. Although the modal analysis found that the second mode frequencies for the standard racket were higher than those of the modified rackets, the experimental results have typically produced lower mode frequencies than those measured by free-free condition modal analysis. It may be possible that the peak is caused by a combination of the second bending and a component of the first torsional mode as they are both of a similar frequency. However, further investigation is required to fully determine the modes responsible for the discrepancies of the second peaks between the standard and novel handled rackets. Higher modes are also observable; peaks discovered at approximately 600 Hz may correspond with the third bending and first string modes and some combination thereof. The peaks at approximately 1000 Hz can reasonably correspond with the second string mode. All these higher modes are of a significantly lower magnitude than those of the first two modes and according to work by Brody (1981); Hennig et al. (1992) and the threshold data from Reynolds et al. (1977b) can be found to be of less importance for player sensitivity and annoyance.

In general, results from two-way independent ANOVA analysis of the subjective ratings suggest that racket F produced the highest perceived ratings of vibration. As no other significant differences were typically found between test rackets, racket F was rated as producing the most vibration.

8.0.4 Subject evaluation

Initial concerns existed that there would be large inter-subject variability between the results for the novel handled rackets. However, similar variations were found for the standard racket, suggesting that the variations were due to human factors instead of racket construction. The effect of subject preferences and shot variations can be clearly observed with the subjective ratings. Not only do the subjective ratings of the racket characteristics (control, power, flexibility and level of vibration) vary for each stroke, but they also vary considerably between subjects. This is indicated by the large standard deviations of the ratings for each subjective characteristic. The individual subject differences were also
clearly observed with the rms measures, with significant differences found between the subjects for all three strokes at both the racket and the knuckle measurements. Figures 7.6 – ?? show the extent of variation and help to explain why varied ratings were attributed to the rackets by each subject. The variations in the rms measures are likely due to differences in technique and physiology between the subjects. However, work by Knudson & Blackwell (2005) found a high degree of consistency of impact kinematics between seven advanced players performing successful topspin forehand drives when provided similar presentation of the ball at impact. If the impact kinematics of the subjects are relatively consistent then it likely that the differences in measured vibration are caused by physiological differences between the subjects and differences in properties such as grip force.

Negative correlations were found between perceived levels of vibration and rating of racket control for both the forehand and serve shot. This relationship helps validate the claim from the structured relationship model, that players felt the level of vibration influenced their perception of control. Within the structured relationship model, players also suggest that too little vibration would also produce a perceived reduction in control. However, this study was not able to identify this threshold point. The Kendall coefficient of concordance was used to show that subjects provided consistent responses for their ratings of control for the volley and forehand, and consistent responses for the level of vibration for serve and forehand. The volley was the only stroke where consistency in rating of power was found.

Thus variations in stroke mechanics between the different strokes may be used to allow subjects to better evaluate certain properties of a tennis racket, variation in stroke mechanics also explain why players prefer to perform a range of strokes to select a racket since single racket strokes are not sufficient to gather sufficient information about a racket's properties. Negative correlations between the ratings of shot performance and vibration rating were observed for each stroke. This suggests a potential influence of the shot performance on the subjective ratings provided. As no significant differences in shot performance for the rackets were found it is possible that this would not have a significant effect on the ratings provided in this study. The role of the shot result must be considered for future studies.

The measurement of damping ratio values was used to determine the rate of attenuation of the vibration at each of the measurement sites. The effect of subjective differences could be observed with the knuckle measures of damping ratio. For all three strokes, significant differences were observable between rackets for the racket throat measures of damping ratio. However, there were no significant differences found between the knuckle damping ratio measurements for each racket. Significant differences between the subject's knuckle damping ratio measures were also found for the forehand and serve. This would suggest that the damping of the vibration measured at the knuckle is also defined by the subject-specific physiology and grip technique, as significant differences between the rackets for the racket throat measures were not found to produce significant differences between the knuckle damping ratio measures.
The correlation of subjective with objective measures did not produce any consistent trends amongst the individual subject correlations. The small number of individual subject measures may have made it difficult for correlations to emerge. By analysing the results for all subjects or by each racket type, it was possible to develop more robust correlations. A further possibility may be that certain subjects are influenced by different aspects of the impact when forming their ratings.

8.0.5 Stroke differences

Shot performance results indicated that the volley was the most successfully performed stroke and the serve was the least successfully performed. The use of a generalised scoring system may not be the most suitable for comparing a variety of strokes. The advantages of this system are that it allows the relative performance of each stroke to be compared, but this may be to the detriment of measuring how effectively each stroke was performed. For example, the serve was found to perform the poorest of the three strokes. This is likely due to the fact that -1 was scored for shots hitting or failing to cross the net. For a serve, there is often a small margin for error; shots hitting the net would occur more frequently than for the other two strokes. Therefore, an improved scoring system would reduce the penalty for serves hitting the net or redefine the scoring criteria for all shots and misses.

Significant differences occurred between a subject's shot performance for the volley only. This may be due to the different styles of play assumed by the test subjects. Players who use a 'serve and volley' style of play may be considered more adept at performing the volley than players classified as 'baseline' players. Correlations can be observed between various racket and knuckle rms measures and the subjective rating of vibration, but only racket throat RMS and knuckle SRMS were found to correlate with standardised vibration ratings for all of the strokes. The least number of correlations between r.m.s measures and vibration rating occurred during this stroke. Measurement methodology for the forehand stroke may not have been appropriate, since in particular it may have been more suitable to measure vibration about two or three axes for the forehand and to compare both the individual axis and combined rms measures to gain a more accurate reflection of what the subject experienced. This is particularly influential on the forehand as players often hit the stroke with topspin (hit the ball with an angled racket face), which could produce considerable vibration about axes which were not measured using the current configuration. During both the serve and volley, players maintained a much straighter angle of impact. Furthermore, in performing the volley, players typically 'blocked' the ball at impact; potentially resulting in the large vibration levels measured. Peaks in the knuckle frequency spectra at around 1000 Hz were only found to be exhibited with the volley stroke. This would suggest that the volley stroke allows a much greater transmission of the higher frequency vibration from impact compared to the serve and forehand. Possible reasons for this include the differences in stroke technique, this includes the grip force applied to the racket
which was unsubstantiated in this test. Other influencing factors can include the stroke differences in body posture, as the flexion of the elbow has previously been shown to influence the transmission of vibration (Burstrom & Lundstrom, 1994).

8.0.6 Evaluation of the racket concept

One of the main purposes of the programme of testing conducted was to investigate a novel design for racket handles using SLS as the method of manufacture. The viability of this concept is discussed in the following points

- The testing was able to show that Duraform PA material is suitable to be used for the manufacture of tennis handles, as all of the rackets experienced at least 200 shots from a highly competent level of players without producing any chronic breakages. Further investigation of the long-term durability of the material is required, but these results do offer confidence in the suitability of Duraform PA for use with sports equipment handles.

- Several players found the novel handled rackets more enjoyable to play with than the standard racket, suggesting that both the material and design were able to produce a suitable impact sensation and that further development of the handle may produce a useful racket technology.

- The concept handles were able to provide a reduction of racket vibration. With the development of the materials and the optimisation of the handle design it may be possible to also improve the level of hand-transmitted vibration.

- The perceived level of vibration was confirmed to influence the perceived level of control. This would suggest that in addition to reducing discomfort from vibration it is possible to improve other perceived racket characteristics by influencing the vibration transmitted to the player.

- The large inter-subject variability showed that each player produced differing vibration results with each racket. Development of the customised aspect of the handle concept may allow the racket handles to be adapted to suit each individual. This would suggest that further research into handle customisation in tennis is worthwhile pursuing.
Chapter 9

Recommendations for further work

This project has investigated an approach to the manufacture of tennis racket handles which can enable a broad range of customisable handle characteristics. A structured relationship model determined racket handle characteristics that were of interest to players, refining the selection of customisable features. From this, a handle concept was selected that modified the vibration experienced from impact. The investigation and development of additional handle concept ideas related to other characteristics identified by the structured relationship model is one avenue of future research. However, this chapter will examine areas of further work directly related to the development and testing of the handle concept featured in this project.

9.1 Player testing

Individual differences between both the impact locations and the vibration measures for each of the test rackets was discovered. Although the cause of differences in impact location has yet to be explained, further investigation can use differing racket construction to determine possible causes. Differences in vibration measures are likely related to the grip and subsequent grip force applied by the player. Work by Schmidt et al. (2006) on golfers discovered the presence of a 'grip force signature' for both expert and beginner golfers. Each player tested produced repeatable traces of grip force applied to the grip of the club, although force profiles varied considerably between players. Further investigation identified the existence of families of grip force signatures. Currently, the existence of grip force signatures has not been determined in tennis. Differences in grip force application for forehand and backhand respectively and between different skill levels have been identified (Knudson, 1991; Knudson & White, 1989; Li et al., 2004), but subjective differences in grip force have not been identified. The grip pressure distribution on a racket handle during a forehand stroke has been investigated (Savage & Subic, 2006), but results are limited to a single player so subjective differences amongst multiple players were not identified. Investigation of individual differences in grip pressure applied to the racket
handle (i.e. 'grip force signatures') in tennis as well as the investigation of signatures for various tennis strokes is an important area of future work.

The investigation of strokes not analysed in the current research is an important area of study. The most notable stroke absent from this study is the backhand. Currently the two-handed backhand is the most popular version of this stroke. To date, the vibration from impact for this stroke has not been investigated. The requirements to measure the vibration at both hands gripping the racket appear to be the major factor preventing research into this stroke. Also a lack of motive to investigate the stroke exists, as it has not been associated with incidents of tennis elbow, unlike the one-handed version. However, the two-handed backhand is a popular stroke in modern tennis and it is important to develop a protocol to investigate this stroke type. The classification of strokes by measurement approach or vibration produced may then be possible.

Future testing should consider the effect of impact sound. Higher frequencies of string vibration are often audible, with the sole effect of string dampers suggested to reduce the sound of vibrating strings (Brody, 1987), since the reduction of sound may be associated with a decrease in hand arm vibration (Stroede et al., 1999). Initial research has already begun in this area with studies relating to means of measurement (Davies, 2005) or removal of the sound of impact (Stroede et al., 1999) experienced by the test subjects. Since both Davies (2005) and Stroede et al. (1999) investigated the relatively sedentary volley stroke situations, their approaches are considered difficult to implement on more dynamic strokes such as the serve. Future testing should aim to consider the sound from impact and the contribution of impact sound to perceived vibration.

Further investigation of player perception should investigate techniques such as paired comparisons (Barrass et al., 2006; Davies, 2005; Roberts et al., 2005) to develop ranked comparisons of rackets for various properties. These tests can determine statistical separation of racket performance data for various characteristics. Comparisons with benchmarked racket measures can be performed to determine the contribution of certain racket properties to player perception.

9.2 Racket testing

A suitable handle design has been developed which has shown the capability of using RM for this application. Some progress regarding optimisation of handle properties has been achieved, however significant effort is still required to bring the concept to market. There are several approaches for the determination of racket properties, including international standard tests, racket professional tests, and racket manufacturer tests. The international standard (Standardization, 1995) is used to determine general racket properties: frame length, weight, handle size, stringbed area, balance point, and inertial characteristics. Many of these key tests are replicated in a similar fashion by devices such as the Babolat racket diagnostic centre (RDC), which is commonly used to determine racket properties by
the research community and racket professionals. The Babolat RDC is used to determine most of the key racket properties for this research.

Several tests used by racket manufacturers to develop and ensure the consistency of racket frames weren’t conducted during this research. The results for the standard Dunlop 200G racket used in this or the detailed protocols for these tests were not provided and therefore it was not possible to replicate these tests during the project. Of the tests conducted by racket manufacturers, three types of tests were identified as useful for future work: flex tests, torque tests and rebound tests.

The flex test used by racket manufacturers typically require an Instron machine and a test fixture with roller of varying separation. Sections of the racket have a constant load applied at a slow rate. The deflection of these sections are measured and used to define the flex of the section (Figure 9.1). Dunlop Slazenger utilise five and seven point bending tests to assess the flex characteristics of the various sections of a racket frame. The modification of rackets to accept the novel handle concept is known to have influenced the flex characteristics of the racket frame, however the role of the handle on current flex measures is unsubstantiated. Further work should aim to examine the current test protocol and modify or add supplementary measurement positions to assess the flex of the handle section of the racket.

Torque tests are typically used to assess the flex characteristics of badminton racket shafts. An example of such a testing device is shown in Figure 9.2. The use of the novel handle concept allows a degree of rotation of the racket frame about the long axis of the handle, but the variability of these measures has not been fully defined. Initial work has been conducted to produce a test arrangement suitable for attachment to the Babolat RDC test device (Figure 9.3). However, refinement of the test procedure and investigation of the effect of varying levels of racket torque are required.

Rebound tests are used by racket manufacturers to examine the coefficient of restitution (COR) of varying frame constructions or string bed patterns. Conventionally, a racket is rigidly clamped in
Figure 9.2: Badminton racket shaft torque test

Figure 9.3: Example of initial tests used to determine handle torque
front of a ball-firing device and the COR of the racket at various impact locations is measured. Kotze (2005) raised concerns over the failure of frames at the handle and throat due to high levels of stress imparted by high ball impact speeds due to the clamp mechanism. Clamp tests were identified as necessary for investigating the handle concept performance as the nature of the device meant that the outer shell of the handle required some element of constraint. The measurement of racket vibrations from impact while in free-fall, using similar techniques to those used by Carroll (1985), was considered inappropriate.

Testing with the rigid clamp immediately produced failure of the novel handles with $21 \text{ ms}^{-1}$ impacts failure occurred in both the SLS handle and the composite shaft around the neck region of the handle concept. The clamp was redesigned with a spring and hinge mechanism to allow movement of the clamp plates at impact to alleviate the problems of high concentrations of stress around the throat region. This clamp permitted the measurement of vibration and racket deflection at impact. As expected, the measures of vibration of the clamped handle were unlike those of a gripped racket (Figure 9.4).

![Vibration traces](image)

Figure 9.4: Vibration traces from three ball impacts for a clamped and hand-held standard racket

The new clamp arrangement allows comparison of rackets with various handle constructions for central impacts. However, off-centre impacts still produced failure with the novel handle. The steel clamp plates do not allow the handle shell to rotate with off-centre impacts, unlike when hand-gripped. Consequently, a large accumulation of torque occurs in the spring elements, resulting in failure. Further racket comparison could be conducted using the modified clamp arrangement, between the clamped racket and a hand-held racket. From initial pilot testing, it is likely that the performance of a clamped racket will not reflect those of a hand-held racket. Further development of the clamp arrangement is required to develop a method for effective benchmark testing of the novel handle concepts. Approaches such as Mohanty & Rixen (2002), who developed a partially clamped condition for modal analysis of racket frames using foam sheets, may provide solutions for a suitable method to be developed.
9.3 Material testing

Little research during this project was directed towards the determination of useful material properties. The lack of knowledge of racket handle performance limited the investigation of material properties.

The Poisson's ratio of Duraform PA is a material property to be defined, as it is used to determine the spring properties of a material. Since SLS materials are anisotropic, investigation of material properties requires testing of parts built in three orientations (Hague et al., 2004). The investigation of the stability of material properties over time and repeated impacts is also required to determine product usability and shelf-life. The damping properties of Duraform PA are another important material property to be defined. Tests such as dynamic mechanical analysis (DMA) of the materials used to construct a conventional and novel handle system can be used to determine both the damping properties of Duraform PA and the material used in a conventional handle, i.e. PU foam. These results can determine whether Duraform provides improved damping regardless of the handle structure used. Further material tests may become evident as the understanding of the handle requirements and development of the handle concept is completed.

One of the major areas of research in rapid manufacturing is that of material development. At present there are available only a limited range of materials suitable for this racket concept. These results obtained using the Duraform PA are encouraging, but extensive testing on the material's durability is still required. Ideally the handle material should exhibit good strength, impact resistance and damping properties.

9.4 Summary

There are numerous avenues of further testing, due to the emerging nature of customised sports grips. Many of the current tennis test procedures have been developed without provisions for customised equipment. Therefore many of the tests need to be modified or redesigned as appropriate, as they do not acknowledge the individual differences in player technique and preference. The results obtained during this project suggest that the customisation of tennis grips is worthwhile pursuing and that increasing developments in RM will serve to improve both the materials and processes with which these customised products can be manufactured. The use of tennis as a candidate sport has also helped to demonstrate that the concept of customised handles or grips may be useful in many sports, especially the other racket sports.
Chapter 10

Conclusions

10.1 Overview of research

The objective of this PhD research was to investigate the use of rapid manufacturing technologies for the development of a customised grip or handle system. Initially, a substantial number of customisable handle features of a racket were identified, and a structured relationship model was developed to help refine the features of a handle to be customised. A single characteristic for customisation was selected and a process of design and testing was pursued. A new handle concept was designed which utilised the flexibility of the SLS process to incorporate arrays of springs elements between the racket handle and a separate handle shell. The concept aimed to influence the vibration experienced by a player from the racket handle. The lack of information regarding vibrational characteristics of racket handles and their influences on player perception limited the process of concept development. Therefore an extensive study of racket performance for three different tennis strokes was undertaken. The intent of the testing was to determine the effects of vibration on subjective perceptions, the differences in vibration characteristics of the various strokes, and the nature of subjective differences for vibration measures and equipment performance.

10.2 Discussion of handle concept

The novel handle concept was developed using SLS to produce enclosed features. This enabled the production of a handle with a series of spring elements enclosed between the handle shell and internal shaft of the racket to separate the handle and racket frame. The ability to add spring elements in such a manner using standard manufacturing techniques is difficult and costly for mass produced sporting implements, and is thus not feasible using conventional approaches. The optimisation and further development of the handle concept was not possible during the course of this PhD as there was not enough information available regarding both the material properties and influences of racket vibration on subject perceptions to define a clear metric of the concept requirements. The handle concept was therefore used to alter the vibration experienced by a player at impact whilst allowing identical racket
frames to be used, ensuring no subtle differences in inertial characteristics, string bed configuration and frame geometry. Due to initial concerns regarding the consistency and performance of the novel handles, a considerable amount of preliminary testing was conducted prior to player testing to ensure that no significant issues of handle construction or performance were reported. Furthermore, the results of the player testing indicated that variability of racket performance was common with both conventional rackets and those equipped with the novel handle concept. As a result, the identification of clear trends for the handle concepts was difficult. While several test subjects reported enjoying using rackets equipped with the novel racket handles, none of the design iterations were found to perform significantly different from the standard racket or any other concept when examining the subjective ratings. The sole exception, racket F was typically found to produce significantly higher vibration ratings than the other test rackets. Examining the vibration measures, rackets equipped with the handle concept almost always produced significantly lower r.m.s measures of vibration at the racket throat. However for knuckle measures, the standard racket often produced significantly lower r.m.s. measures than those of the rackets equipped with the novel handle concept.

10.3 Limitations of research

10.3.1 Structured relationship model

The structured relationship model was found to be a useful tool for directing this research towards handle characteristics that players acknowledged influence their perception of racket performance and comfort. Yet limitations of this method are found as the structured relationship model only represents the responses of the population of subjects tested. The internet questionnaire attempted to broaden the applicability of this model by determining the relative importance and preferred levels of the various characteristics from a larger more diverse sample group. However, it was apparent from this procedure that certain handle or grip properties are difficult to investigate without providing the respondent with a physical stimulus to determine their response. In particular properties such as grip wrap material and handle shape were poorly represented by this method of testing. Given the tactile properties of the racket handle, it is more favourable to allow subjects to manipulate rackets of varying wrap material or handle shape in order for them to fully develop a response to these characteristics. The extension of the structured relationship model protocol to various sample populations would be a possible method of satisfying these limitations.

10.3.2 Player test results

The results, as mentioned in Chapter 9, did not address or control the grip force and sound from impact during the testing. Therefore the effect of these two properties on the measured and perceived vibration was not controlled. The accelerometer arrangement used for the testing only measured single
axis vibration and was positioned normal to the racket face. For strokes, such as the forehand, this method may have not been appropriate as the impacts typically employed an inclined racket face. Furthermore, to ensure player comfort and familiarity with the racket, only one accelerometer was attached to the racket frame. While this allows vibrations experienced by the racket from the bending modes to be measured, the position at the centre of the racket is not optimal for the measurement of the torsional racket loads as the central sections of the racket experience the least torsion. A more suitable placement would incorporate accelerometers at positions around the shoulder or edges of the racket head allowing measurement of the torsional deflections experienced by the racket. However, this requires the incorporation of at least one (preferably two) further accelerometer to the racket frame in addition to the continued measurement of the vibrations due to racket bending at locations such as the racket throat or handle. The use of identical racket frames was advantageous for maintaining consistent racket properties. Significant differences in impact location were observed between subjects but not observed between the test rackets. Comparisons of various racket constructions would help determine whether the impact location is defined by the racket construction or subject's technique.

10.3.3 Handle concept

The current limitations of the handle concept are caused by the lack of sufficient information to further develop and enact the customised design. To optimise the design of the handle concept, further information regarding material properties of SLS suitable materials are required. However, the specific properties cannot be fully defined until the requirements of the handle design are produced. Another problem with the concept is related to the enclosed nature of the springs. While this is one of the novelties of the handle concept, this produces problems when attempting to detect failure of the springs. Unless the failure occurs in springs towards the butt-end of the handle it is difficult to observe failure of individual spring elements until the failure becomes catastrophic. The use of methods such as X-rays are not suitable for determining the presence of damaged spring elements, due to the large number of springs housed within the handle. Therefore, 3D imaging methods may be required to examine for any breakages within the arrays of spring elements.

Player tests were not able to fully define the reasons between the difference in frequency of the second noticeable peaks of the frequency spectra between the standard and novel rackets. Further testing and development of alternative testing methodologies will be required to achieve this.

10.4 Final conclusions

There are many studies investigating the vibration experienced by a player or tennis racket whilst performing a specific racket stroke. Typically these studies are concerned with the effect of vibration on the symptoms of tennis elbow or the performance of vibration reducing racket technology. However,
only a narrow range of strokes have been investigated for these tests, often using simulated stroke conditions which negate the individual differences in technique. By examining three different tennis strokes, this study determined significant differences between each of the three strokes. The existence of significant differences between strokes suggests that results of tennis studies can be considered stroke specific. It also suggests that future testing should approach each stroke with a different methodology as the most suitable test conditions may not be shared with the other test conditions. Investigating the individual subject results, significant differences for both impact location and measured level of vibration were evident, although frequency spectra for impacts with each racket were found to be relatively consistent. To date only Hennig et al. (1992) has reported the existence of substantial differences between subjects for vibration magnitude when testing various rackets. The individual differences in measured vibration explain the varied subjective ratings of the rackets, indicating that preferences may be based upon individual perceptions rather than a formulaic approach. It is unclear whether subjective differences for impact location are caused by subjects impacting close to the location of preferred impact sensation for their own racket or the adjustment of impact location producing the preferred impact sensation for each racket. Further investigation with differing racket constructions is required to define this.

Although torsional vibration from off-centre impacts was not measured, the results of this study show that the impact location between racket and ball along the longitudinal axis of the stringbed produces a much greater effect on the bending vibration of the racket frame than impacts deviating laterally across the stringbed. This behaviour was supported by clear identification of the effect of impact at nodal points along the string bed on the magnitude of first mode vibration.

The measurement of the ratio of vibration decay also suggests that perceived racket differences may be determined by initial measures of vibration at the knuckle. For all strokes, correlations between knuckle SRMS (first 0.02 seconds of vibration) measures and vibration rating were found. No significant differences were found between the rackets for each subject for knuckle damping ratio measures, even though significant differences existed between the subjects for damping ratio measures. This would suggest that the rate of decay of hand measured vibration is influenced by physiological factors of the subject, or that the differences of the test rackets in this study were not large enough to produce significant differences in decay at the hand. It would therefore appear that subjects determined racket vibration from the initial shock of the impact, signified by the SRMS measure. For the frequency content, analysis of the correlations between subjective vibration magnitudes and magnitudes of the frequency peaks of four frequency ranges for all strokes found correlations between the subjects perceived level of vibration and the first frequency range. This is in agreement with work by Brody (1981, 1987); Hennig et al. (1992) since the first mode of the tennis racket can be considered most influential on players perceived level of vibration.
The results from this study help confirm some influences of impact vibrations on player evaluation of a racket, and details important issues regarding the development of technology for improving player comfort using tennis rackets. This research also provides further evidence to support the design and development of personalised equipment in sport, as clear individual differences in the sensations experienced by players exist. Future work may be able to determine the principal causes of the significant differences between subjects and therefore begin the implementation of customised racket handles effectively.

Overall the project has shown that the concept of customised handles for tennis rackets has potential value. The significant differences displayed between the subjects using the same rackets supports the notion that it is not possible to generically design equipment that is suitable for everyone. The introduction of customisation may allow a small number of generic rackets frames to be used with individualised handle constructions to provide a more appropriate alternative. Although significant future research regarding the handle concept has been identified, it is encouraging to show that the method of construction and the handle concept have both been successfully implemented on tennis rackets, with some players preferring the novel handle concept rackets versus the standard racket. With continued development customised handles may become applicable for a wide range of sporting implements.
References


Appendices
Appendix A

Structured relationship model: Test sheets
INTERVIEW GUIDE

Subject No:- _______  Date:- ________
Name:- ___________________________  Age:- ________

INTRODUCTION

I would like to begin by thanking you for agreeing to participate in this interview study. As part of the project we are talking to level 3 coaches about their perceptions of racket handles and grips.

I am using a recording system to ensure complete and accurate information, as well as providing a more efficient interview process. The recording is necessary so that a transcription of our conversations can be produced for later analysis.

During the testing I would like you to think about the feel and performance of each grip or racket handle. Upon completion of the test, please describe in your own words your perception of the 'feel' or performance of the grip or handle. It is important that you try and explain as clearly as you can the reasons behind your perceptions and the feedback you are receiving from using the grip/handle during each test.

Do you have any questions so far?

TESTING

Firstly, I would like you to complete a standard 5 - minute warm-up. Please play as you would do prior to the start of a match, incorporating differing shots in your routine. After you have completed the warm-up I want you to describe your perceptions of 'feel' for that grip or handle.

Suitable Questions:

- How did you find the 'feel' of the grip?
- How the grip feels in the hand?
- How suitable is the grip to your game?
- What did you like about the grip/handle?
- What did you dislike about the grip/handle?
- How would you improve the grip/handle?

Which grips/handles did you prefer?

Did the impacts 'feel' any different with any of the handles/grips?
Descriptors Used:
GRIP SELECTION

What Racket do you use? ________________________________

Why do you use that Racket?

How long have you used that brand?

What Grip(s) do you use? ________________________________

Why do you use that grip?

What do you like about the 'feel' of that grip?

How could the 'feel' of the grip be further improved?

When you consider changing grip, what characteristics do you look for?
CONCLUDING QUESTIONS

Are there any important factors we failed to discuss?

Did I lead or influence your responses in any way?

Did the recording equipment inhibit or affect you in any way?

Have you any comments or suggestions about the interview itself?

Finally, some questions about your background.

How old are you?

At what age did you take up Tennis?
Appendix B

Structured relationship model: general dimensions and model

B.1 General dimension quote trees
<table>
<thead>
<tr>
<th>QUOTES</th>
<th>HIGH ORDER SUB-THEME</th>
<th>HIGH ORDER THEME</th>
<th>DIMENSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>actually have been able to make a cleaner contact cause it felt like I had a better purchase on the racket rather than anything differently.</td>
<td>IMPACT EFFORTLESS</td>
<td>IMPACT</td>
<td>EFFORT</td>
</tr>
<tr>
<td>When I tend to go full that when the grips are not as stick so when we sit like that it feels a little lighter on the contacts and I move my racket head through a little quicker</td>
<td>IMPACT HARDWORK</td>
<td>IMPACT</td>
<td>AFFECT ON RACKET POWER</td>
</tr>
<tr>
<td>felt when I was hitting the ball it didn’t turn like the weight into the ball</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>Wound it a lot of effort to put into the ball to try and get over the net really</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“felt that I would struggle on contact, I didn’t feel like I would have a firm contact at all”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“1 felt that grips like really small you can move the racket head a little quicker you can like get the racket head through quite quick on the forehand”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“n the smaller the grip the smoother that you get and feel the larger the grip you like the more it was going to be”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“the racket before hand was really fast I think the length and the stiffness was kind of perfect to me but just makes the racket feel a bit too light and airy”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“It gives you like better grip on the racket and it got a little bit more power as well”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“This racket felt a bit lighter than the others … it a bit lighter so I feel you get more of a swing on there less weight, you’ve got less control”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“this one felt a bit lighter when I hit the ball lighter swing really I could get the racket head through”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“I liked the two that I could swing while this one didn’t feel the ball anymore it felt too light on impact”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“hit it felt too light and after a couple of shots I was a bit of the ball at the same time”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“hit your hand down as you hit the ball because of the impact, the strength of the ball just increases your hand down as you are hitting the ball”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“there’s some grips were when you’re playing you hit a forehand and you hit your hand up so it makes the shot a little more accurate”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“this quite a different shape when you get the impacts in sort of wider area on your hand”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“uncomfortable, sticks in your hand, haven’t really got a true feeling over the ball, it doesn’t feel a bit different over the impacts”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“I just felt uncomfortable, couldn’t really swing through, it kept panning to the side on impact couldn’t really follow through at all”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>and then you hit it down onto your hand a bit especially when hitting the mean harder shots you’ve got a lot more impact in the hand so I think that would probably annoy you actually if you played with too long”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“Pretty solid actually, very good indeed. A good feedback off it really, quite solid”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“I might actually have been able to make a cleaner contact cause it felt like that better purchase on the racket other than anything differently”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“quite hard though. I felt it starting to work after a while, probably due to the vibration you there’s really not really any giving so there’s your getting quite a lot of vibration”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“left this writing when I was hitting at times the racket didn’t absorb much of the vibration”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>I think there was a bit too much sort of sponginess in there it took away all the vibrations which means you have less control, couldn’t feel the racket on the ball and the strings really it was all taken up on the grip”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“it was just a bit too big and a bit too spiny really and it took quite a lot of the vibration and the control and feel away from the racket”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
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<tr>
<td>“it was just a bit too big and a bit too spiny really and it took quite a lot of the vibration and the control and feel away from the racket”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“it was different over the impact … there’s a bit more vibration, its not really accurate”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“They did feel different; they felt as though there were little more up my arm”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
<tr>
<td>“it just stopped all the way up to my arm it wasn’t like one sudden job, just after you hit the ball you could feel it fall down the racket and into your elbow”</td>
<td>IMPACT</td>
<td>IMPACT</td>
<td>RACKET WEIGHT</td>
</tr>
</tbody>
</table>

The racket was quite heavy, good for serving with and you had some control
<table>
<thead>
<tr>
<th>QUOTES</th>
<th>HIGH ORDER SUB-THEME</th>
<th>HIGH ORDER THEME</th>
<th>DIMENSION</th>
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<tr>
<td></td>
<td>LARGE HANDLE SIZE</td>
<td>SECURITY OF GRIP ON HANDLE</td>
<td></td>
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<td></td>
<td>SMALL HANDLE SIZE</td>
<td>REQUIREMENTS OF HEEL PAD</td>
<td>FIT IN HAND</td>
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<td></td>
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<td>REQUIREMENTS OF FINGERS</td>
<td>GRIP FACTORS</td>
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<td></td>
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<td>SHAPE OF PALLET/HANDLE</td>
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<td>HANDLE SHAPE PROFILE</td>
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<td></td>
<td>SHAPE AT BASE</td>
<td>VS. REST OF HANDLE</td>
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<td></td>
<td></td>
<td>WIDTH ACROSS GRIP</td>
<td></td>
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<tr>
<td>&quot;I mean with improper big tool feel a bit more power feel ... whereas slightly smaller you feel more of the racket as though you quite get enough of that, but at same time thing like serve and volley and big not gives style would suit&quot;</td>
<td></td>
<td></td>
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<tr>
<td>&quot;It's just really big, it's hard to get a good grip. It's so massive, it's quite hard to get your wrist as so big&quot;</td>
<td></td>
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<tr>
<td>&quot;It's just a big grip, one of the ones you try tennis elbow, I could play with it but I would prefer not to&quot;</td>
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</tr>
<tr>
<td>&quot;I wouldn't fit in my hands so my hand is actually too small to get around as so it was too hard for me to actually fit the serve with it unless want to be twisting my wrist a lot, it is going to injure me&quot;</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>&quot;...the smaller the grip, the more whip that you get and feel the larger the grip you like the more snug is against power that you tend imply with...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;I use a small handle rather than a large one if you can't get onto the same size cause you can place your hand around it and get more on the racket so obviously when you're hitting I think you will have a firmer grip so you are less likely to miss hit cause the control less likely to waver in your hand cause you've got a better grip&quot;</td>
<td></td>
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<tr>
<td>&quot;The whole size of the grip is a bit small you know but that's been a bit more of the size of having more elbow for increasing the grip too tight too small a grip&quot;</td>
<td></td>
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<tr>
<td>&quot;...because of the ridge I feel I cannot secure my hand quite strongly quite securely on the grip area...&quot;</td>
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<tr>
<td>&quot;...it doesn't really feel right to the control of it, like the whole racket meant to fit with your hand and it but that's too rough, my nerve was going all over the place...&quot;</td>
<td></td>
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<tr>
<td>&quot;...the ridge was too round too small for your edges and when you move you're moving it as it's going around your hand...&quot;</td>
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</tr>
<tr>
<td>&quot;...it felt a bit more expensive cause it's quite a thin grip and I felt I need a little bit more grip to get my hand or really any way you can wear it quite fast...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the biggest thing for me are I have a feel on the tools or so really feels loose at the bottom of the racket almost like it would come out of the hand...&quot;</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>&quot;...it's quite soft so when you pick it up flick your wrist sometimes and it can easy into the bottom of your hand when you're serving with the one being soft it doesn't seem to do that and its easier to get a tighter grip...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...it's lacking grip it actually gives a bit where in some you can just feel the handle and it's quite uncomfortable...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...and you really don't feel that hands to get your hand behind already I feel good with, with I didn't think I will be long with that one and a wonderful performance terribly uncomfortable...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;When I've had half of that, that sort of thing of the ridge so my thumb is feeling a different texture in my three fingers and that seem to affect me for some reason...&quot;</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>&quot;When you've got hard pitches then you've got some fingers are gripping tighter than other fingers and when you get one finger gripping tighter than the other you haven't got a firm grip and the racket head crowns... probably be better towards the bottom but some sort of action at the top on my fingers cause when I serve my fingers higher up on the grip...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the bottom is like the backhand feel for instance you actually feel quite a bit with the bottom fingers...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...it also feels the same as if the round was a bit well thanks not much shape as is sort just feel...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...it was very different cause to kind of much more circular as opposed to having your little fingers...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the grip is really thin and there are so many angles on them that you just don't know where to put your hand, it is a ridge...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...I think it's the shape cause in the hexagonal less moves to the less control as well...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
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</tr>
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<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
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<td></td>
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</tr>
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<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
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</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;...the grip are reflected and there are so many angles on them that you just don't know where to put your hand, if it is a ridge...&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
"...the right grip so that the racket face was exaggerated in a position so that I couldn't control the tennis ball.'

"...usually that would be my forehand grip but on this it's like a backhand grip so if you try and hit a forehand it's going to slip right and hit the net.'

"...left as though it was sliding more and the spinning off the racket was all wrong really, where you tried to position it would do something different sort of.'

"...it's hard to get the feel of the racket in the right place, you have to think about more.'

"I don't like much about it. It's just hard to line up the racket face and swing, it's really hard to be accurate with it.'

"I think also with the grip I dictate a lot with my left hand on the throat of the racket so I know where the racket face is.'

"...it's a good idea with the when you've got the edge it gives you a little bit more awareness of exactly where your grip is. I think it would be very easy to slightly even judge your grip if you haven't got these kind of thumb positions that you have normally got.'

"...very restricted in grip selection, limits your two to three extreme grips on both sides which is quite restrictive and you feel as if you actually had to look at the racket position as opposed to the feel of the grip.'

"I didn't like the way it sat in your hand, just sits very uncomfortably cause it sticks on your hand and sits off.'

"...left hand is really hard to get a nice feel as a feel when you pick up a racket you want it to feel nice and the shape getting on with your hands.'

"...very important there just where you sit for the different grip changes, where the bottom of your thumb happens as a result.'

"It's a bit slippery when your hands get sweaty its prone to slipping out of your hand. these type of grips, they used to when I used to play with them.'

"...the feel is very slippery and it feels like serving it was going to come out of my hand and leave the racket.'

"...I would prefer something that is quite tacky umm cause I don't hold on too it (the handle) lightly.'

"...when you're hitting shots you have a firmer grip so you are less likely to miss so cause the racket less likely to move in your hands cause you've got a firmer grip.'

"...well basically when I was hitting a back hand to change my grip to my forehand I felt it hard work to hit. I could feel it in my wrists when I was changing from back hand to forehand.'

"...well basically when I was hitting a back hand to change my grip to my forehand I felt it hard work to hit. I could feel it in my wrists when I was changing from back hand to forehand.'

"...every time I went for a shot your brain is telling you to go to that movement there.'

"...with it being a quite a thick towel and quite hard to change grips you can really feel the grip when you are going from back hand to forehand.'

"...changing grips its all the same just easier to change grip when it's uniform.'

"...Serves it was very tough cause you can't get your normal service grip you have to get really hard you arm right round.'

"...I think it for the serve cause you can snap your wrist with it while holding the grip quite well.'

"...too small. So again on the serve it just needs to be a bit bigger cause the balance between power and spin.'

"...I do feel as though my wrist and grips to have to be stronger especially on the volley cause of the sharp end of the grip is actually going through my fingers.'

"...hurt on the volleys and on the serve actually hurt the Rogers cause when the pressure went though if you like the side we was going through my fingers and there so when it hurt it actually came into the fingers and hurt a little bit.'

"...it makes it harder to flick your wrist on your forehand if the grips too big cause your hands like not as close as it should be and you need a good grip on the racket handle.'
B.2  Internet questionnaire
Racket grip and handle perception survey

1. Demographic Questions

Thank you for agreeing to complete this questionnaire. I am very grateful for your time. Please remember to answer the questions with your honest opinion as there is no right or wrong answer. Your responses are to be treated with the strictest confidence.

Name (optional):

Age:

Club (optional):

Number of years played tennis:

Coaching Qualifications:

Number of years qualified:

LTA Rating:

Frequency of play:

Next >>

Racket grip and handle perception survey

2. Equipment Questions

Racket:

Handle Size:

Strings

String Tension used:

Grip Wrap used:

Overgrip used:

Frequency of grip wrap or overgrip change:

Do you use any vibration absorbing device?

If Yes, what device?

Racket Weight (if known):

Balance point of racket (if known):

<< Prev  Next >>
Racket grip and handle perception survey

### Forehand shot

During an 'ideal' forehand shot, ...........

<table>
<thead>
<tr>
<th>How much effort would you expect to execute the shot?</th>
<th>How important is the perceived effort you put into the shot?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum effort</td>
<td>1</td>
</tr>
<tr>
<td>---------------</td>
<td>---</td>
</tr>
<tr>
<td>How would you expect the impact to 'feel' in your hands?</td>
<td>How important is the dead/lively feel in your hands from impact?</td>
</tr>
<tr>
<td>Dead</td>
<td>1</td>
</tr>
<tr>
<td>How much vibration would you expect to 'feel' at impact?</td>
<td>How important is the vibration you 'feel' from impact?</td>
</tr>
<tr>
<td>No vibration</td>
<td>1</td>
</tr>
<tr>
<td>How should the racket weight feel during the stroke?</td>
<td>How important is the racket weight during the stroke?</td>
</tr>
<tr>
<td>Light</td>
<td>1</td>
</tr>
</tbody>
</table>

### Backhand shot

During an 'ideal' backhand shot, ...........

<table>
<thead>
<tr>
<th>How much effort would you expect to execute the shot?</th>
<th>How important is the perceived effort you put into the shot?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum effort</td>
<td>1</td>
</tr>
<tr>
<td>How would you expect the impact to 'feel' in your hands?</td>
<td>How important is the dead/lively feel in your hands from impact?</td>
</tr>
<tr>
<td>Dead</td>
<td>1</td>
</tr>
<tr>
<td>How much vibration would you expect to 'feel' at impact?</td>
<td>How important is the vibration you 'feel' from impact?</td>
</tr>
<tr>
<td>No vibration</td>
<td>1</td>
</tr>
<tr>
<td>How should the racket weight feel during the stroke?</td>
<td>How important is the racket weight during the stroke?</td>
</tr>
<tr>
<td>Light</td>
<td>1</td>
</tr>
</tbody>
</table>
**Racket grip and handle perception survey**

**First serve**

During an 'ideal' first serve,

<table>
<thead>
<tr>
<th>How much effort would you expect to execute the shot?</th>
<th>How important is the perceived effort you put into the shot?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum effort 1 2 3 4 5 6 7 8 Shot hardwork 9</td>
<td>Not at all important 1 2 3 4 5 6 7 8 Extremely important 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How would you expect the impact to 'feel' in your hands?</th>
<th>How important is the dead/lively feel in your hands from impact?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead 1 2 3 4 5 6 7 9 Lively 9</td>
<td>Not at all important 1 2 3 4 5 6 7 8 Extremely important 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How much vibration would you expect to 'feel' at impact?</th>
<th>How important is the vibration you 'feel' from impact?</th>
</tr>
</thead>
<tbody>
<tr>
<td>No vibration 1 2 3 4 5 6 7 8 Lots of vibration 9</td>
<td>Not at all important 1 2 3 4 5 6 7 8 Extremely important 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>How should the racket weight feel during the stroke?</th>
<th>How important is the racket weight during the stroke?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light 1 2 3 4 5 6 7 9 Heavy 9</td>
<td>Not at all important 1 2 3 4 5 6 7 8 Extremely important 9</td>
</tr>
</tbody>
</table>

<< Prev  Next >>
In relation to the configuration of the racket handles and grip

Rank these characteristics of the grip wrap in order of their importance on the grip wrap you use with your racket (1 = most important, 3 = least important)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbency of wrap material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durability of wrap material (how long wrap maintains its initial properties)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How well wrap attaches to handle/quickly releases wrap</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please add any other characteristics that influence your choice:

How do you prefer your grip surface to feel?

<table>
<thead>
<tr>
<th>Smooth</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Textured</th>
</tr>
</thead>
</table>

How important is the feel of the grip surface to you?

<table>
<thead>
<tr>
<th>Not at all important</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Extremely important</th>
</tr>
</thead>
</table>

How influential is the wrap material on the grip you hand makes on the racket?

<table>
<thead>
<tr>
<th>No influence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Extremely influential</th>
</tr>
</thead>
</table>

How much does the wrap surface/texture influence your transition between different grips when making shots?

<table>
<thead>
<tr>
<th>No influence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Extremely influential</th>
</tr>
</thead>
</table>

Please rank the following grip factors in order of importance for you when gripping the racket (1 = most important, 5 = least important)

<table>
<thead>
<tr>
<th>Fit of handle in fingers</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit of handle in palm of hand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Definition of handle edges/handles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handle butt cap size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width across grip (width between two edges of handle perpendicular to racket face)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please select any of the following words that correspond to feelings that you like to experience from your racket grip:

- STICKY
- SPONGY
- DRY
- VELVETY
- KNOBBLY
- BILKY
- SMOOTH
- RUBBERY
- Tacky
- PLASTICY
- PEACHY
- ROUGH
- Other (please specify)

How important are these grip feelings to you?

<table>
<thead>
<tr>
<th>Not at all important</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Extremely important</th>
</tr>
</thead>
</table>
Appendix C

Analysis of novel handle concept: Test sheets
Information sheet

Customisation of sports grips using rapid manufacturing technologies

The study you have volunteered to take part in has the purpose of investigating player perception of impact from differing racket handle constructions. The investigation will be conducted with five different rackets plus your own racket. The only difference between the rackets will be that of the construction of the handle.

During the tests the following data will be recorded:

Age
First name
Years of experience
Current racket properties (weight, balance point, dynamic inertia, racket flex)
Scaled responses to vibration feel from impact
Vibration measures from racket grip and knuckle

A code will be assigned to you to identify all data recorded from your test sessions. All recorded personal information will be kept anonymous to parties other than the investigators to ensure your confidentiality.

The study will be conducted in the following manner:-

• You will be assigned four rackets per test period.
• You will perform two test sessions, with two test periods per test sessions. The four strokes under investigation are the cross-court forehand, the slice backhand, the serve and the forehand volley.
• With each assigned racket you will be required to play 8 of the selected stroke (5 for serves). The ball will be fed to you using a Bola ball cannon.
• After each shot the impact location will be noted, you will be asked to rate the feel of the shot. After completing 8 shots with each racket you will be asked to provide a scaled response for four questions relating to your perception of the impact experienced with the racket used.
• Upon the completion of 8 shots with a racket, the next assigned racket will be used until all 4 of the assigned rackets have been tested. Then you will progress to the next stroke. You will only be required to perform two strokes per test session.

For the duration of the test you will have an accelerometer attached, using double sided tape, to the first knuckle of your gripping hand. You will also have an accelerometer positioned under your gripping hand. The cables from these accelerometers will be run up your arm to to allow them to feed into a data acquisition system. This system will be set-up to produce minimum annoyance you, the arrangement can be altered if you find it uncomfortable.

The complete test should take place over two separate test sessions; each test session should last no longer than one hour.

Any queries please contact:

David Barrass - D.F.Barrass@lboro.ac.uk tel:- 01509 227679
In relation to the configuration of the racket handles and grip:

Rank these characteristics of the grip wrap in order of their importance on the grip wrap you use with your racket (1 = most important, 3 = least important).

<table>
<thead>
<tr>
<th>Abrasiveness of wrap material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability of wrap material (how long wrap maintains its usable properties)</td>
</tr>
<tr>
<td>How well wrap attaches to handle/existing underwrap</td>
</tr>
</tbody>
</table>

Please add any other characteristics that influence your choice:

How do you prefer your grip surface to feel?

- Smooth
- Textured

How important is the feel of the grip surface to you?

Not at all important | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Extremely important | 9 |

How influential is the wrap material on the grip your hand makes on the racket?

No influence | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Extremely influential | 9 |

How much does the wrap surface/texture influence your transition between different grips when making shots?

No influence | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Extremely influential | 9 |

Please rank the following grip factors in order of importance for you when gripping the racket (1 = most important, 5 = least important):

<table>
<thead>
<tr>
<th>Fit of handle in finger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit of handle in palm of hand</td>
</tr>
<tr>
<td>Definition of handle edges/voids</td>
</tr>
<tr>
<td>Handle built-up size</td>
</tr>
<tr>
<td>Width across grip (width between two edges of handle perpendicular to racket face)</td>
</tr>
</tbody>
</table>

Please select any of the following words that correspond to feelings that you like to experience from your racket grip:

- STICKY
- SPONGY
- DRY
- VELVETY
- SILKY
- SMOOTH
- RUBBERY
- Tacky
- PLASTIC
- PEACHY
- ROUGH
- Other (please specify): [space]

How important are these grip feelings to you?

Not at all important | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Extremely important | 9 |
How much vibration did you feel in your hands?

No vibration

1 2 3 4 5 6 7 8 9 Lots of vibration

1) 2) 3) 4)
## PLAYER TESTING FORM

**SUBJECT NO:**

**STROKE:**

**RACKET ORDER:**

---

### How much control did you feel you had?

<table>
<thead>
<tr>
<th>No control at all</th>
<th>Maximum control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td></td>
</tr>
</tbody>
</table>

### How powerful did the shot feel?

<table>
<thead>
<tr>
<th>No power at all</th>
<th>Maximum power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td></td>
</tr>
</tbody>
</table>

### How did the racket feel?

<table>
<thead>
<tr>
<th>Racket flexible</th>
<th>Racket stiff</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td></td>
</tr>
</tbody>
</table>

### Did you experience any discomfort during the shot?

<table>
<thead>
<tr>
<th>No discomfort</th>
<th>Very uncomfortable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9</td>
<td></td>
</tr>
</tbody>
</table>

---

### RACKET CONTROL

<table>
<thead>
<tr>
<th>Racket Trial</th>
<th>Player Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

### RACKET POWER

<table>
<thead>
<tr>
<th>Racket Trial</th>
<th>Player Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

### RACKET FEEL

<table>
<thead>
<tr>
<th>Racket Trial</th>
<th>Player Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

### DISCOMFORT

<table>
<thead>
<tr>
<th>Racket Trial</th>
<th>Hand</th>
<th>Wrist</th>
<th>Elbow</th>
<th>Shoulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix D

Experimental modal analysis

D.1 Introduction

Experimental modal analysis is used to determine the vibration characteristics of the test rackets. The use of modal analysis to evaluate the vibration characteristics of sports equipment is common with studies completed for golf (Roberts et al., 2001; Varoto & McConnell, 1995), baseball (Noble & Walker, 1994; Russell, 2006), football (Ronkainen & Harland, 2006), tennis rackets (Casolo et al., 2000; Fyson, 1998; Mohanty & Rixen, 2002; Oh & Yum, 1986), and tennis balls (Davies, 2005).

These techniques have been used by Brody (1981, 1987) and Segesser (1985) to investigate the natural frequencies of tennis racket frames. Results from these studies have shown that the first bending mode of a tennis racket frame lies in the 120-200 Hz and 80-200 Hz range respectively.

Several studies (Mohanty & Rixen, 2002; Noble & Walker, 1994; Oh & Yum, 1986) have also used the modal analysis to identify the position of nodal points on the sporting implement, identifying the point at which minimum vibration is produced on impact (sweet spot). Davies (2005) used modal analysis of various types of tennis ball to identify the natural frequencies linked to the sound and vibration produced from impact.

D.2 Experimental modal analysis

Modal analysis can be used to determine the vibration characteristics (mode shapes and natural frequencies) of a structure. The response of the structure is different at each of the different natural frequencies, with the deformation patterns being known as mode shapes. Every point on a structure will have the same resonant frequencies, but the phase and amplitude will change providing different mode shapes. The mode shape differs for each natural frequency, with higher natural frequencies possessing more nodes (regions of zero amplitude) on the structure. Both the mode shape and natural frequencies (which are dependent on the mass and stiffness distributions within the structure) are used to help design structural systems for noise and vibration applications (Ewins, 2006).

To determine the mode shapes and natural frequencies of the structure using modal analysis, sets of Frequency Response Functions (FRFs) are obtained. Different techniques are used to carry out modal analysis, but all methods require the force and response to be measured. Typically there are two methods for exciting a structure and measuring the response. Fixed response, with moving excitation or moving response with fixed excitation. Although both these approaches were used in preliminary testing, fixed excitation with a moving response was found the most suitable for racket measurements. The method of fixed excitation involves exciting the structure at a fixed point. In this case, an electromagnetic shaker was attached via a stinger to a point on the racket frame. A signal generator is used to excite the structure at the necessary frequencies. One drawback of the fixed excitation method is the necessity to attach the excitation device to the structure. Stingers (thin
attachment devices) are used to help reduce the attachment influence on the structure. However, there always exist some constraining effects and mass loading of the structure (Ewins, 2006).

The objective of the data acquisition and processing mechanism is to measure the signals developed by the sensing mechanism and then to calculate the magnitude and phases of the excitation force and response. This is performed by signal analysers, based on Fast Fourier Transform (FFT) algorithms, which provide direct measurements of the FRFs. From these FRFs, modal frequencies and mode shapes can be identified.

**D.2.1 Methodology**

The natural frequencies of the test rackets, configured as in Table 6.4, were determined when suspended in a free-condition as shown in Figure D.1.

![Figure D.1: Racket and shaker suspended in free-condition](image)

Brody (1987); Brody et al. (2002) demonstrated that when gripped, a tennis racket behaves more akin to a freely suspended racket than a rigid clamped racket due to the action of the wrist. With a clamped racket producing much lower frequency 'diving-board' mode shapes. All test rackets were freely suspended to produce mode shapes representative of a hand-held racket.

Each tennis racket frame was suspended using light strings at four points on the frame; two strings at the shoulders of the racket frame were used to suspend the racket from the ceiling and two strings attached at the buttcap of the handle passed through a large weight directly below the racket to anchor the racket in position. The arrangement of these support strings prevented twisting and unnecessary movement of the racket. Natural frequencies of the string system were determined to be between 30–45 Hz, much lower than the first mode of the racket frame. A small light nut was glued to the racket frame at the 1 o'clock position of the racket frame (point 16 of the racket model), see Figure D.2. Preliminary testing found that this point produced good excitation of both lateral and torsional modes.

To excite the test rackets, an electromagnetic shaker (LDS model V201/3) was freely suspended using a separate free-standing structure. The shaker was suspended from the structure using two light
Figure D.2: Nut and nut attachment point on suspended racket

pieces of string (Figure D.1). The metal stinger was threaded into the nut on the racket and then attached into the stinger’s chuck mechanism. Care was taken to ensure that the racket and stinger were at the same height as the shaker so that minimal loading of the racket frame occurred.

The racket frame was represented as a 33-point model. Small circular pieces of Scotchlite reflective tape were attached at various points around the racket frame to provide a suitable representation of the frame shape in the software (Figure D.1). The Scotchlite tape provides a visible position for the measurement points and increases the effectiveness of the laser measurement. The model points were connected as appropriate in the software to produce a racket frame model (Figure D.3).

Figure D.3: Racket model created in Polytec SLDV software

Measurements of the racket points were performed using a scanning laser doppler vibrometer (SLDV) (Polytec OFV 056), see setup in Figure D.4. The use of a laser vibrometer is preferred as it allows non-contact measurement of the displacement of each point, thereby reducing the loading effects of using devices such as accelerometers. The SLDV operates using two orthogonally aligned mirrors to allow the scanning head to measure multiple points in a single acquisition, without the need to move the scanning head. The scanning head was calibrated to the racket position and range of measurement points so that all points were measured in a single capture. The SLDV measured each of the model points progressively, with 10 measures taken at each point of the model and averaged the 10 measures to produce the result. To determine the modal frequencies of the racket frame, the racket was initially excited with a pseudo-random excitation of amplitude 7V. The resulting frequency response function (FRF) showed peaks at the modal frequencies. Centre frequencies and bandwidth of each of these peaks was noted. Using sine-wave excitation of 7V amplitude at each of the centre frequencies with appropriate bandwidth, each of the modal frequencies was measured to determine racket mode shapes.
D.2.2 Results

The results of the experimental modal analysis are shown in Table D.1. Five modal frequencies were found to produce clear mode shapes. Although higher modal frequencies are likely to exist (especially for the strings), they are of reduced amplitude and are therefore harder to determine. These higher frequency mode shapes are typically of little importance to tennis research.

Table D.1: Identified modal frequencies for each of the test rackets

<table>
<thead>
<tr>
<th>Racket</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid body mode</td>
<td>38.3</td>
<td>42.2</td>
<td>32.0</td>
<td>32.8</td>
<td>32.8</td>
</tr>
<tr>
<td>1st Bending Mode</td>
<td>123.4</td>
<td>112.5</td>
<td>112.0</td>
<td>110.5</td>
<td>112.5</td>
</tr>
<tr>
<td>2nd Bending Mode</td>
<td>290.7</td>
<td>245.5</td>
<td>258.6</td>
<td>250.0</td>
<td>240.6</td>
</tr>
<tr>
<td>1st Torsional Mode</td>
<td>313.3</td>
<td>306.3</td>
<td>315.6</td>
<td>306.0</td>
<td>290.6</td>
</tr>
<tr>
<td>3rd Bending Mode</td>
<td>567.2</td>
<td>587.5</td>
<td>593.7</td>
<td>593.8</td>
<td>654.7</td>
</tr>
</tbody>
</table>

The modes discovered at approximately 40 Hz are known as rigid body modes and are produced by the system used to suspend the rackets. The fundamental modes of the racket range from 110 Hz to 123 Hz, with the standard racket possessing a higher fundamental frequency. These values agree with published values of the fundamental modes of composite racket frames (Brody, 1981; Cross, 2000; Hennig et al., 1992; Kotze, 2005). The precise frequencies depend largely on the mass and stiffness of the frame (Brody, 1995). Differences in fundamental frequencies are likely caused by the assembly of the novel handle concept, which has produced rackets with small variations in mass and inertia properties. In addition, small discrepancies in stringbed tension can also yield effects on the racket frame stiffness.

Although Brody (1981, 1987) suggests that the vibrations of a tennis racket that seem to be particularly bothersome are caused by the first harmonic mode of oscillation, the higher modes were measured to allow the assessment of their contribution. Figure D.5 shows examples of the mode shapes for each of the measured modes.

D.3 The effect of strings

All of the rackets were strung at the test tension (60 lbs) for the modal analysis of the test racket frames as preliminary testing found that the presence of strings reduced the modal frequencies of the racket frames. This was in agreement with Cross (2001).
Preliminary tests were conducted to investigate the most appropriate method to conduct the experimental modal analysis of the racket frames. The effect of the strings was investigated using the same racket suspension method previously discussed, but the racket response was instead measured with a small piezo-resistive accelerometer (Bruel & Kjaer 4375V) attached to each of the measurement points. The response was measured using SignalCalc data acquisition system and a 33 point model was constructed in Smart Office to analyse the FRFs. A standard Dunlop 200G frame was used for the testing. The racket frame was strung at 249 N (56 lbs) and 289 N (65 lbs), the highest and lowest recommended tensions for the frame and was also tested unstrung. Table D.2 compares the results of the three racket configurations.

Table D.2: The effect of strings on the modal frequencies of a tennis racket

<table>
<thead>
<tr>
<th>Stringing condition</th>
<th>1st Bending</th>
<th>2nd Bending</th>
<th>1st Torsional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstrung</td>
<td>131.0</td>
<td>383.6</td>
<td>386.7</td>
</tr>
<tr>
<td>249 N</td>
<td>123.8</td>
<td>334.5</td>
<td>370.5</td>
</tr>
<tr>
<td>289 N</td>
<td>123.9</td>
<td>335.5</td>
<td>364.1</td>
</tr>
</tbody>
</table>

Table D.2 indicates that the strings noticeably reduce the modal frequencies, but that the string tensions produce little appreciable difference on the racket modal frequencies. Cross (2001) found that the fundamental vibration frequency of of a tennis racket frame decreases by about 10% when strings are added, depending on the stiffness of the frame and the string tension. It is not merely the effect of the additional mass that produces this trend, but the tension of the strings also applies a load to the frame in a direction that helps to increase displacement of the frame and therefore reduce the stiffness.

Experimental modal analysis of the string bed was also investigated in preliminary testing to examine the mode shapes and approximate frequencies of the string modes. For this test, the 200G racket was again used and was strung at a tension of 249 N. A 34 point model of the string bed was created, using Scotchlite circles to again locate the measurement positions. For the string modal analysis, a similar test setup to the test racket modal analysis was used, except a standard laser doppler vibrometer was used (Polytec OFV323). This required the scanning head to be moved manually to each measurement point, with 10 samples acquired at each point. The model and results were processed in Smart Office and the string modes and frequencies were produced (Figure D.6).

The methodology for measuring the string modes was found to be difficult to perform. Several studies (Li et al., 2004; Stroede et al., 1999) have found that no effect of string vibration on subject perception or discomfort. Thus modal frequencies for the string beds were not determined for each test racket. Also, due to constantly changing the nature of strings, tensions will alter over the course
of the test. Although tensions are not expected to be appreciably different for each subject, changes are likely to affect the modal frequencies.
Appendix E

Individual results for rms and damping ratio measures
Figure E.1: Subjects RMS measures for each of the test rackets
Figure E.2: Subjects SRMS measures for each of the test rackets
Figure E.3: Subjects MaxRMS measures for each of the test rackets

(a) Forehand racket measures

(b) Forehand knuckle measures

(c) Serve racket measures

(d) Serve knuckle measures

(e) Volley racket measures

(f) Volley knuckle measures
Figure E.4: Subjects Damping ratio measures with each of the test rackets used (bars represent ± 1 s.d.)
Appendix F

Analysis of novel handle concept: Individual impact locations
Figure F.1: Subject impact locations versus standard vibration rating for forehand
Figure F.2: Subject impact locations versus standard vibration rating for forehand (continued)
Figure F.3: Subject impact locations versus standard vibration rating for serve
Figure F.4: Subject impact locations versus standard vibration rating for serve (continued)
Figure F.5: Subject impact locations versus standard vibration rating for volley
Figure F.6: Subject impact locations versus standard vibration rating for volley (continued)