Determination and analysis of dimensions of ‘feel’ in tennis ball impacts

This item was submitted to Loughborough University’s Institutional Repository by the/an author.

Additional Information:

- A Doctoral Thesis. Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University.

Metadata Record: https://dspace.lboro.ac.uk/2134/10759

Publisher: © Gareth Davies

Please cite the published version.
This item was submitted to Loughborough University as a PhD thesis by the author and is made available in the Institutional Repository (https://dspace.lboro.ac.uk/) under the following Creative Commons Licence conditions.

For the full text of this licence, please go to: http://creativecommons.org/licenses/by-nc-nd/2.5/
Please note that fines are charged on ALL overdue items.
DETERMINATION AND ANALYSIS OF DIMENSIONS OF 'FEEL' IN TENNIS BALL IMPACTS

by

Gareth Davies

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy of Loughborough University

2005

© by Gareth Davies (2005)
Abstract

The modern style of tennis has been played for over a hundred years and although the ball has developed such that today it is a consistent product, no structured analysis has ever been undertaken to determine players' perceptions of ball qualities. This study aims to develop a comprehensive understanding of the characteristics that contribute to a player's perception of 'feel' of a tennis ball and in addition to investigate the suitability of various test procedures and data analysis methods for studies of this nature.

A series of impact tests were completed to characterise the mechanical properties of selected tennis balls. A single-degree-of-freedom viscoelastic ball model was developed, and through the use of a numerical integration solution, values of stiffness and damping, peak force and contact time were reported for impact velocities of 16-66m/s.

To establish how such differences between balls may be perceived, an interview study was completed on a group of sixteen elite tennis players in order to determine their perception of 'feel' of a tennis ball. The resulting interviews were structured to form eight dimensions of 'feel'.

Two subsequent experiments were completed into the sound and vibration at impact, with both experiments capturing synchronous subjective perceptions and objective data in a realistic playing environment. In order to capture the subjective perceptions, the method of paired comparisons was adopted that allowed the reliability of the players to be evaluated through the analysis of their responses. Suitable objective metrics were determined for the analysis of sound and vibration data.

Significant correlations were found between subjective perceptions and objective metrics for both sound and vibration experiments. It was found that the strongest correlations between the subjective data and objective metrics were obtained for those players deemed reliable, highlighting that generally only skilled test subjects are capable of such fine discriminations between balls.
Firstly I would like to thank my two supervisors Professor Steve Rothberg and Professor Roy Jones for their continual support, advice and guidance throughout the project.

Thanks are also extended to the Sports Technology Research Group in providing assistance during testing and in particular Dr. Jon Roberts, Colin Young and Andy Statham.

In addition I would also like to thank the many technical staff involved in the development of instrumentation for the project who include Alan Wilkinson, Steve Carr and Nev Carpenter. I would also like to extend my gratitude to all of the tennis players who freely gave up their time to participate in this research study.

I would also like to thank Dunlop Slazenger International Ltd. for their funding of this research, as well as their invaluable input in the selection and provision of balls for use during this study. I would also like to extend my gratitude to Brian Machin for his advice and input at review meetings.

On a personal note, I would like to thank my family and Sarah without whom, this thesis would never have been written.
Publications Arising From This Work

# Contents

## Chapter 1
### Introduction ................................................................. 1
  1.1. Tennis equipment ...................................................... 1
    1.1.1. The racket ....................................................... 2
    1.1.2. The tennis ball ................................................. 3
  1.2. The impact between ball and racket .............................. 5
  1.3. The ‘feel’ of sporting equipment .................................. 6
  1.4. Research objectives ................................................ 8
  1.5. Thesis outline ........................................................ 9

## Chapter 2
### Dynamic Properties of Tennis Balls ............................... 11
  2.1. Dynamic testing of sports balls ................................... 11
    2.1.1. Coefficient of restitution ..................................... 12
    2.1.2. Contact time .................................................. 13
    2.1.3. Coefficient of friction ........................................ 14
    2.1.4. Other dynamic tests .......................................... 15
  2.2. The tennis ball impact .............................................. 16
    2.2.1. Modelling of the tennis ball impact ........................ 17
  2.3. Test equipment and protocol ...................................... 20
    2.3.1. Calibration of equipment ..................................... 21
      2.3.1.1. Normal impacts ........................................... 21
      2.3.1.2. Oblique impacts .......................................... 23
    2.3.2. Testing protocol .............................................. 24
  2.4. Analysis of normal impacts ....................................... 25
    2.4.1. Fitting the SDOF viscoelastic model ....................... 25
    2.4.2. Normal impact results ........................................ 28
    2.4.3. High speed video of normal impacts ....................... 32
  2.5. Analysis of oblique impacts ..................................... 33
  2.6. Experimental modal analysis ..................................... 36

## Chapter 3
### Elicitation of Perception of ‘feel’ in Tennis Ball Impacts ....... 39
  3.1. Previous studies in the elicitation of perceptions in sports psychology ................................................................. 39
  3.2. Interview technique .................................................. 41
  3.3. Interview structure ................................................... 43
    3.3.1. Testing scenario ............................................... 43
    3.3.2. Equipment design .............................................. 44
    3.3.3. Participant selection .......................................... 44
    3.3.4. Interview guide ............................................... 46
  3.4. General dimensions of ‘feel’ of a tennis ball .................. 47
    3.4.1. Ball sound ...................................................... 48
    3.4.2. Feeling from impact ........................................... 50
List of Figures

Chapter 1
Figure 1.1 – Ball type classification
Figure 1.2 – Prediction of ‘feel’ from dynamic properties (Haake et al., 2003)

Chapter 2
Figure 2.1 – Dynamic COR against incoming ball speed
Figure 2.2 – Tennis ball force profile obtained by Cross (2000)
Figure 2.3 – Inversion of the contact region (Cross, 1999)
Figure 2.4 – Model of viscoelastic impact (Babitsky & Veprik, 1998)
Figure 2.5 – Stiffness and damping for various ball types (Haake et al., 2003)
Figure 2.6 – Viscoelastic impact model fit (Goodwill & Haake, 2004)
Figure 2.7 – Viscoelastic impact model fit (Babitsky & Veprik, 1998)
Figure 2.8 – Kister force transducer (Kistler cutting force measurements)
Figure 2.9 – Ball canon adjustable frame
Figure 2.10 – Model of a force transducer with additional top and bottom masses
Figure 2.11 – Force plate mounted in canon with impact hammer strike, raw force plate output and corrected force plate output
Figure 2.12 – Averaged accelerometer output, raw and corrected force plate output for Slazenger ball at 16m/s
Figure 2.13 – Model fit at various speeds
Figure 2.14 – Stiffness values for Tretorn ball
Figure 2.15 – Ball dynamic properties
Figure 2.16 – Comparison of results obtained from this study and that by Haake et al. (2003) also indicating ITF regulations for static stiffness
Figure 2.17 – Peak force plotted against stiffness for Fort Plus ball
Figure 2.18 – High speed images of normal impact
Figure 2.19 – Comparison of pressurised and pressureless ball for impact at high velocity
Figure 2.20 – View of contact area for a Tretorn ball at 59.67 m/s
Figure 2.21 – Oblique force plate angles
Figure 2.22 – Averaged accelerometer output, raw and corrected tangential force plate output for Slazenger ball at 25m/s for oblique impact at 15°
Figure 2.23 – Normal peak forces obtained for a Tretorn ball at all oblique angles
Figure 2.24 – Normal component of velocity plotted against normal peak force for Tretorn ball
Figure 2.25 – Tangential peak forces obtained for a Tretorn ball at various oblique angles
Figure 2.26 – Normal and tangential component of velocity plotted against tangential peak force for Tretorn ball
Figure 2.27 – High speed video image of oblique impact of Slazenger ball at 18m/s
Figure 2.28 – Variation in COF for a Fort Plus ball during impact at 25m/s at an impact angle of 15°
Figure 2.29 – Tennis ball modal analysis experimental setup
Figure 2.30 – Sample frequency response function of a tennis ball
Figure 2.31 – Mode shape of first natural frequency of an incompressible sphere (Shannon & Axe, 2002)
Chapter 3
Figure 3.1 – Interview test equipment
Figure 3.2 – General dimension - Ball sound
Figure 3.3 – General dimension – Feeling from impact
Figure 3.4 – General dimension – Bounce
Figure 3.5 – General dimension – Control
Figure 3.6 – General dimension – Appearance
Figure 3.7 – General dimension – Ball wear
Figure 3.8 – General dimension – Ball flight
Figure 3.9 – General dimension – Player’s psychology
Figure 3.10 – Tennis ball ‘feel’ map
Figure 3.11 – Questionnaire responses for ideal ‘feel’ of a tennis ball

Chapter 4
Figure 4.1 – Normal equal-loudness-level contours for pure tones (ISO 226:2003)
Figure 4.2 – Effect of duration on the threshold of pure tones (Yost, 1994)
Figure 4.3 – Effect of masking bandwidth on signal threshold (Moore, 2003)
Figure 4.4 – Width of critical bands as a function of centre frequency (Levine, 2000)
Figure 4.5 – Relationship between perceived loudness in sones and the intensity level of a sound Levine, 2000)
Figure 4.6 – Commonly used sound weighting networks
Figure 4.7 – Sound pressure discrimination measured in terms of the Weber fraction for various SPLs and frequencies of sound (Coren et al., 1999)
Figure 4.8 – Effect of bandwidth on loudness (Moore, 2003)
Figure 4.9 – Difference threshold for frequency as a function of frequency (Yost, 2004)
Figure 4.10 – Weber fraction for frequency discrimination
Figure 4.11 – Cross-section of skin showing the dermis and epidermis (Griffin, 1990)
Figure 4.12 – Threshold of perception curves for various studies (Roberts, 2002)
Figure 4.13 – Measurement locations for transmissibility tests (Reynolds & Angevine, 1977)
Figure 4.14 – Average values transmissibility curves for vibration for a 9N finger grip (Reynolds & Angevine, 1977)
Figure 4.15 – Calculated ratios of the vibration levels at the elbow divided by the vibration levels at the wrist (Reynolds & Angevine, 1977)
Figure 4.16 – Bones of the right hand and arm (Tortora, 1995)
Figure 4.17 – Anatomical and basicentric coordinate systems for hand transmitted vibration (ISO 5349-1:2001)
Figure 4.18 – Frequency weighting curve for hand-transmitted vibration (ISO 5349:1, 2001)

Chapter 5
Figure 5.1 - Cumulative probability vs. Score/n
Figure 5.2 – Racket mounted accelerometer
Figure 5.3 – Vibration grip adaptor
Figure 5.4 – Accelerometer skin mounting configuration
Figure 5.5 – Mounting frequency response
Chapter 6
Figure 6.1 – Subjective analysis methodology
Figure 6.2 – Bradley Terry model fit for sound experiment
Figure 6.3 – Results of t-tests for sound data
Figure 6.4 – Bradley Terry model fit for vibration experiment

Chapter 7
Figure 7.1 – Balls sound spectra
Figure 7.2 – Sample sound data capture
Figure 7.3 – Sound decay curve
Figure 7.4 – Peak-to-peak values for all balls used for each player
Figure 7.5 – Average sound spectra for a single player
Figure 7.6 – Sample vibration measurements for each measurement location
Figure 7.7 – DRMS grip values for all balls used for each player
Figure 7.8 – Frequency spectra for each measurement location

Chapter 9
Figure 9.1 – HSV of Slazenger ball at 40m/s showing deformation of front and back of ball
Figure 9.2 – 3DOF tennis ball model
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3DOF</td>
<td>Three-degree-of-freedom</td>
</tr>
<tr>
<td>Absorber</td>
<td>Dunlop Absorber</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Force plate calibration factor</td>
</tr>
<tr>
<td>$c$</td>
<td>Damping coefficient</td>
</tr>
<tr>
<td>$c_0$</td>
<td>3DOF damping coefficient</td>
</tr>
<tr>
<td>COF</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>COP</td>
<td>Centre of percussion</td>
</tr>
<tr>
<td>COR</td>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>DRMS</td>
<td>Dynamic Root Mean Square</td>
</tr>
<tr>
<td>$f_i$</td>
<td>Centroid of a frequency spectrum</td>
</tr>
<tr>
<td>$F_m$</td>
<td>Measured output of force plate</td>
</tr>
<tr>
<td>$F_N$</td>
<td>Normal force</td>
</tr>
<tr>
<td>Fort Plus</td>
<td>Dunlop Fort Plus</td>
</tr>
<tr>
<td>$F_T$</td>
<td>Tangential force</td>
</tr>
<tr>
<td>$H$</td>
<td>Cumulative distribution function</td>
</tr>
<tr>
<td>HSV</td>
<td>High-speed video</td>
</tr>
<tr>
<td>ITF</td>
<td>International Tennis Federation</td>
</tr>
<tr>
<td>$k$</td>
<td>Stiffness</td>
</tr>
<tr>
<td>$k_0$</td>
<td>3DOF cover stiffness</td>
</tr>
<tr>
<td>LTA</td>
<td>Lawn Tennis Association</td>
</tr>
<tr>
<td>$m_c$</td>
<td>Critical value of t-test</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of judges in paired comparison experiment</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of questions in paired comparison experiment</td>
</tr>
<tr>
<td>$p$</td>
<td>Probability</td>
</tr>
<tr>
<td>Precision</td>
<td>Dunlop Precision</td>
</tr>
<tr>
<td>$r$</td>
<td>Pearson correlation coefficient</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SDOF</td>
<td>Single-degree-of-freedom</td>
</tr>
<tr>
<td>$s_i$</td>
<td>Magnitude of a frequency spectrum at frequency $f_i$</td>
</tr>
<tr>
<td>Slazenger</td>
<td>Slazenger Wimbledon</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound pressure level</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>Loss factor</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Impact angle</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Combined grip vibration</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Coefficient of consistence</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Damped natural frequency</td>
</tr>
<tr>
<td>$V$</td>
<td>Bradley Terry merit value</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Undamped natural frequency</td>
</tr>
<tr>
<td>Wilson</td>
<td>Wilson US Open</td>
</tr>
<tr>
<td>$\dot{x}_0$</td>
<td>Initial velocity</td>
</tr>
<tr>
<td>$X_1$</td>
<td>Acceleration in x-direction of grip</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Acceleration in z-direction of grip</td>
</tr>
<tr>
<td>$X_3$</td>
<td>Acceleration at knuckle</td>
</tr>
<tr>
<td>$X_4$</td>
<td>Acceleration at grip</td>
</tr>
<tr>
<td>$X_5$</td>
<td>Acceleration at elbow</td>
</tr>
<tr>
<td>$z$</td>
<td>Normalised variables</td>
</tr>
</tbody>
</table>
The modern style of tennis has been played for over a hundred years and although the ball has developed such that today it is a consistent product, no structured analysis has ever been undertaken to determine players' perceptions of ball qualities. Typically ball improvements are sought in terms of performance characteristics such as longevity or consistency, however such improvements may be lost if the player 'feels' physically or psychologically uncomfortable whilst using the equipment (Roberts et al., 2001a). This research study aims to develop a systematic approach to the elicitation and analysis of players' perceptions of tennis balls and in addition to develop test procedures to obtain objective data in a realistic tennis playing environment that may be correlated with the subjective perceptions. This is turn will enable desirable product design parameters to be identified, and hence 'feel' may be engineered into the design process.

1.1. Tennis equipment

Tennis is a game that has its origins in the 12th century and was referred to in religious texts as 'jes de paume', the game of the palm, because it was played with the bare hand. This game eventually became known as real tennis, played indoors, in large galleries with jutting roofs and points were won according to how the ball was played off of the gallery walls. However since that time the introduction of modern materials has transformed the equipment and game to such an extent that the governing body is considering attempts to limit the progression of equipment with the possibility of returning to the dimensions of old wooden rackets (Shine, 2003).
1.1.1. The racket

In the early days of the game the hand was used to hit the ball. Developments in the game led to gloves being used with players eventually starting to use short bats. The tennis racket by 1500 was no longer completely made of wood but consisted of a wooden handle with a sheep gut strung head. Whilst the basic shape of tennis rackets has remained relatively unchanged, the introduction of metals and subsequently graphite and carbon fibre allowed the ability to eliminate and relocate weight because of the materials’ higher stiffness and strength-to-weight ratios. As a product of these changes, oversize heads could be produced which allowed greater racket power due to the longer strings and in addition improved off-centre strikes due to the stabilising influence of weight at a greater distance from the centreline of the racket (Brody et al., 2002).

As the racket is likely to have a large bearing on the overall ‘feel’ of a shot, it is vital to limit its effect in this study where the ball is the primary concern. Where objective measurements are being made, differences between rackets are likely to be as large as, or larger than, the differences between balls. Therefore during each set of objective tests only one racket will be used such that its effect will remain constant for all players. As elite players are the focus of the study, a standard ‘tour’ racket was chosen, which would be familiar to all the players. Two rackets were required for two separate test protocols, both displaying similar properties. The properties of both rackets were determined through the use of a Babolat diagnostic machine, and are presented in Table 1.1 alongside typical values of a wooden racket (Dunlop Maxply) and an oversize beginner’s racket (Wilson Hammer) for comparison. It is apparent that the tour rackets have a smaller head size than a beginner’s racket for manoeuvrability, are slightly heavier in weight and have an increased string tension for additional control. The wooden racket has a small head size, is very flexible and has a low string tension. Both flexibility and stringbed tension are unitless but allow direct comparisons to be made between rackets on the diagnostic machine.
1.1.2. The tennis ball

Tennis balls in the early days of tennis were made of leather stuffed with hair or wool. Starting in the 18th century, ¾" strips of wool were wound tightly around a nucleus made by rolling a number of strips into a little ball. String was then tied in many directions around the ball and a white cloth covering sewn around the ball. With the introduction of lawn tennis in the 1870’s, vulcanised rubber was first used to manufacture balls (Lawn Tennis Association, 2005).

The modern tennis ball is comprised of two major parts, the inner core and the outer cloth covering. The inner core is constructed of two half-shell pieces of formed rubber, which are joined together with adhesive to form a single core. Two dumbbell shaped pieces of cloth are attached to the ball core by adhesive to give the tennis ball its classic appearance. The thickness and density of the ball cloth is matched to the court type for which the ball is designed.

The balls currently in use can be subdivided into two categories of pressurised and pressureless. A pressurised ball is constructed when the core is filled with air (or a gas such as nitrogen) at a pressure that is above the ambient pressure. These balls lose their pressure, and hence playing properties, over time. A non-pressurised ball is made from a thicker rubber core, and the pressure within the core is equal to the ambient air pressure. These balls tend to hold their playing characteristics for a longer period of time, as it is only the cloth that deteriorates.

In 1999, the International Tennis Federation (ITF) approved an experiment in which two new types of tennis ball would be permitted for use in tournaments (Coe, 2000). The two types of ball were designed to have different performance characteristics derived from their differing dynamic and aerodynamic properties. With the

<table>
<thead>
<tr>
<th>Racket Type</th>
<th>Weight (g)</th>
<th>Head Size (sq cm)</th>
<th>Flexibility</th>
<th>Stringbed tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunlop 200G</td>
<td>342</td>
<td>612</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Dunlop 300G</td>
<td>298</td>
<td>632</td>
<td>60</td>
<td>58</td>
</tr>
<tr>
<td>Dunlop Maxply</td>
<td>376</td>
<td>512</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>Wilson Hammer</td>
<td>264</td>
<td>818</td>
<td>73</td>
<td>33</td>
</tr>
</tbody>
</table>

Table 1.1: Babolat diagnostic centre racket results
introduction of the two new types of tennis balls (type I and III) there are now three types of ball available for play, type I, II and III. The ball construction for all three ball types can be either pressurised or pressureless as they are classified through measurement of the diameter of the ball and a compression test, which measures the forward and return deformation of the ball under an applied load. Type 1 balls are harder than the traditional type II balls and are designed for slow pace courts such as clay. Type III balls are larger in diameter by approximately 6-8%. Research shows that they are slower through the air due to their increased drag properties, and in addition have a steeper rebound angle both giving more time for the receiver to collect the ball (Coe, 2000). Figure 1.1 displays how the three ball types react to a court.

Current regulations imposed by the ITF restrict the colour of the ball to yellow or white and the seams of the tennis ball must be stitchless. Strict limits are also in place for the mass and diameter for each type of tennis ball, and in addition quasi-static tests are used to determine the ball's static stiffness and coefficient of restitution (COR) through a rebound test. Appendix A gives further information regarding the testing procedure and limits for each type of tennis ball. Whilst these tests have the advantage of simplicity, (the rebound test was introduced in 1925 and has remained unchanged since) they may not represent how a ball performs under actual playing conditions. Incident ball speeds in the rebound test of 7m/s are far short of those found at the top echelons of the male game.

For this research study, tennis balls were chosen that were likely to display the largest differences. The balls, all of which conform to ITF regulations, were chosen through correspondence with industry specialists with extensive ball player testing experience (Gillard, A. Personal communication, November 2001). The balls are listed in Table 1.2 together with the results of a series of tests completed as per the ITF ball testing guidelines, outlined in Appendix A.
<table>
<thead>
<tr>
<th>Type</th>
<th>Mass (g)</th>
<th>Diameter (mm)</th>
<th>Rebound (cm)</th>
<th>Forward Deformation (mm)</th>
<th>Return Deformation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunlop Absorber</td>
<td>56.7</td>
<td>64.8</td>
<td>147</td>
<td>5.44</td>
<td>7.52</td>
</tr>
<tr>
<td>Dunlop Fort Plus</td>
<td>58.1</td>
<td>64.9</td>
<td>140</td>
<td>5.92</td>
<td>8.28</td>
</tr>
<tr>
<td>Dunlop Precision</td>
<td>Oversize</td>
<td>57.9</td>
<td>67.6</td>
<td>136</td>
<td>5.89</td>
</tr>
<tr>
<td>Slazenger Wimbledon</td>
<td>Pressurised</td>
<td>57.8</td>
<td>64.9</td>
<td>146</td>
<td>6.2</td>
</tr>
<tr>
<td>Tretorn TXT</td>
<td>Pressureless</td>
<td>56.4</td>
<td>64.1</td>
<td>141</td>
<td>5.82</td>
</tr>
<tr>
<td>Wilson US Open</td>
<td>Pressurised</td>
<td>57.1</td>
<td>63.8</td>
<td>150</td>
<td>6.71</td>
</tr>
</tbody>
</table>

Table 1.2: Balls used in the study

1.2 The impact between ball and racket

The impact location on the racket is likely to have a large bearing on the overall ‘feel’ of a shot, with a tendency for off-centre strikes to ‘feel’ bad. This has led to a definition of a sweet spot as an impact point on the racket where it ‘feels’ good (Brody, 1987). In practise, however, a number of sweet spots exist on a racket each relating to a different physical phenomenon. One location of a sweet spot is where the coefficient of restitution (COR) is at its greatest, and hence maximum ball speed is attained. A second sweet spot is defined as the centre of percussion (COP); an impact at this point results in no resultant force on the hand. A final definition of the sweet spot is the location of the node of the fundamental mode of the racket. An impact at this point does not excite modes of vibration in the implement (Brody, 1981; Cross, 1998). In practise, however, all three sweet spots are likely to be located in a similar region close to the centre of the racket face, and it is unlikely that a player could distinguish between them.

There are many different strokes that can be used in tennis to create contact between the ball and racket. 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. The varying grip employed, ball impact speed and action of each stroke may result in various perceptions for the players. As it is clearly not possible to analyse all of the shots and the various methods of playing them, shots have been chosen in this study which improve the consistency of the test. Perhaps the easiest shot to analyse is the serve, as the ball does not need to be delivered prior to impact and for an elite player the impact location is extremely consistent. In addition it is at the serve where the largest impact speeds are present and where the differences between balls may be
emphasised. Whilst this shot may be ideal for some test structures, the sharp movements involved may be problematic for heavily instrumented rackets and players. Certain shots, such as the punch volley played at the net typically require less rapid movements. Whilst losing some favour in the modern game, the volley is still seen as a vital shot in any player’s repertoire, and is suited to applications where movement may be restricted or hampered.

A further factor to consider in the analysis of the racket/ball impact is the relative speed of impact. Tennis is a game where impact speeds vary from high service speeds to deft touch shots played at the net. It may be the case that the ‘feel’ of balls is more apparent at different speeds, so it is useful to be aware of typical ball impact speeds. Table 1.3 outlines the results of a study of ball speeds which have been determined through the analysis of a series of points from a male elite player (Cislunar Aerospace, Inc, 1998).

<table>
<thead>
<tr>
<th>Shot Type</th>
<th>Speed before racket impact</th>
<th>Max speed after impact</th>
<th>Pre-bounce speed</th>
<th>Post-bounce speed</th>
<th>Speed before opponent impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serve</td>
<td>-</td>
<td>53.6</td>
<td>38.9</td>
<td>27.7</td>
<td>24.1</td>
</tr>
<tr>
<td>Forehand service return</td>
<td>26.8</td>
<td>29.1</td>
<td>17.9</td>
<td>13.4</td>
<td>10.7</td>
</tr>
<tr>
<td>Backhand service return</td>
<td>21.5</td>
<td>29.1</td>
<td>17.9</td>
<td>13.4</td>
<td>10.7</td>
</tr>
<tr>
<td>Forehand</td>
<td>8.5</td>
<td>34.0</td>
<td>21.9</td>
<td>15.2</td>
<td>13.9</td>
</tr>
<tr>
<td>Backhand</td>
<td>7.6</td>
<td>30.8</td>
<td>21.9</td>
<td>14.3</td>
<td>12.5</td>
</tr>
<tr>
<td>Forehand volley</td>
<td>17.0</td>
<td>21.0</td>
<td>13.9</td>
<td>9.8</td>
<td>8.5</td>
</tr>
<tr>
<td>Backhand volley</td>
<td>18.8</td>
<td>19.7</td>
<td>15.2</td>
<td>9.4</td>
<td>8.5</td>
</tr>
<tr>
<td>Overhead volley</td>
<td>11.2</td>
<td>49.2</td>
<td>39.8</td>
<td>27.7</td>
<td>24.1</td>
</tr>
</tbody>
</table>

Table 1.3 – Ball speeds (m/s) per shot type based on an elite male player (Cislunar Aerospace, Inc, 1998)

1.3. The ‘feel’ of sporting equipment

Tennis players often comment on the ‘feel’ of a tennis ball when it is hit, through the use of subjective language. The language used is typically poorly defined with the perceptions described being formed from a complex combination of factors including
the sensations of the hands, the speed and trajectory of the ball, the time the ball spends on the racket and the sound at impact. In addition, some perceptions are likely to be affected by the appearance of the ball, as well as external influences such as background noise and even mood. As perception may be defined as the human interpretation of a physical stimulus, it is possible that the same stimulus results in differing perceptions for different players.

In order to further the understanding of the ‘feel’ of sports equipment a number of studies have attempted to relate engineering objective data to subjective perceptions, with the aim of identifying those characteristics that contribute to ‘feel’. However the methods for capture of subjective perceptions have varied significantly in terms of methodology and complexity.

In the first set of studies, anecdotal evidence was used to hypothesise a link between the subjective perceptions and objective data. Haake et al. (2003) in studying the relationship between the dynamic properties of tennis balls and their perceived ‘feel’ plotted a graph of dynamic COR against dynamic stiffness identifying a trend of increasingly good ‘feel’, as displayed by the arrow in Figure 1.2. A variety of ball types were used including a punctured and pressureless ball, both of which were assumed to have a bad ‘feel’. Whilst this study goes some way to highlight how ‘feel’ may be affected by the dynamic properties of tennis balls, it fails to provide any actual subjective perceptions to substantiate the hypothesis.

A second group of studies utilised simple response scales to elicit subjective perceptions e.g. Noble & Walker, 1994; Merkel & Blough, 1999; Stroede et al., 1999. Stroede et al. (1999), in studying the effect of string vibration dampers on the perceived discomfort of impact, obtained discomfort ratings when balls were fired at a stationary racket held by the test subject. A visual scale was used to capture the subjective perceptions labelled from ‘comfortable on impact’ to ‘uncomfortable on impact’. The results were used to determine which factors contributed to the perceived discomfort of the impact. Whilst these studies all collected subjective information from their test subjects, the questions used identified the perceptions of discomfort, pain and shot quality only in terms of ‘good’ or ‘bad’. It is apparent from
Hocknell et al. (1996) that the ‘feel’ of sporting equipment is a complex issue and it is clear that these studies oversimplify the concept.

In the third set of studies, a more in-depth view of ‘feel’ was considered where more than one characteristic that may contribute to the overall ‘feel’ is investigated e.g. Kuwano et al., 1999; Roberts et al., 2001a, 2001b; Roberts, 2002. Kuwano et al. (1999) completed a study of the perception of sound for a golf impact. However, rather than just recording pleasure or discomfort, questions were used that assessed all qualities of the perceived sound such as ‘hard-soft’, ‘sharp-dull’ and ‘vivid-dead’. In addition, Roberts et al. (2001a) completed an in-depth interview study to determine important characteristics of ‘feel’ for golf impacts. The results of the study were used to develop further objective tests to investigate the factors found to be important, such as the ball contact time (Roberts et al., 2001b).

It is clear that, of those studies completed, only Kuwano et al. (1999) and Roberts et al. (2001a, 2001b, 2002) have adequately addressed the complex nature of the ‘feel’ of sporting equipment. Whilst the ‘feel’ of a tennis ball impact is likely to be similarly complex in nature, it is also likely that different factors will be apparent to those found in golf. Therefore a study is required to elicit the important characteristics of ‘feel’ for a tennis ball impact. Armed with this knowledge suitable tests may be devised that will be capable of eliciting suitable perceptions that may be correlated with objective data. In addition the differences found between tennis balls are likely to be more subtle than those between golf clubs. Methods of subjective perception elicitation will need to be devised that allow small differences to show themselves, as well as evaluating the consistency of the subjective results obtained.

1.4. Research objectives

This study aims to develop a comprehensive understanding of the characteristics that contribute to a player’s perception of ‘feel’ of a tennis ball, and to determine the relative importance of each of the characteristics. In addition, this study aims to investigate the suitability of various test procedures and data analysis methods for studies of this nature.
In order to correlate the subjective perceptions with the sensations received by the player at impact, a series of tests are required that allow direct measurement of the stimulus received by the players. This study aims to develop valid test procedures that replicate as closely as possible actual playing conditions, with subjective and objective data collected at the same time. For analysis of the subjective data, this study aims to develop methods that allow subtle differences between balls to be detected and evaluated, as well as a method of reliability evaluation for each of the judges used in the experiments. Suitable objective analysis techniques will also be developed that take into account the human sensitivity to sound and vibration. Techniques will also be developed that allow the link between the subjective and objective data to be fully evaluated.

Finally this study aims to identify the properties of the balls that are responsible for each of the 'feel' characteristics with the aim that 'feel' may be engineered into the design process of tennis balls.

1.5. Thesis outline

This thesis is comprised of eight subsequent chapters that report the methods, analysis and findings of various studies into the perception of 'feel' of tennis balls. The outline of the thesis is as follows:

Chapter 2 analyses the dynamic properties of tennis balls through a comprehensive series of force plate tests. Parameters such as the ball contact times and peak forces are obtained directly from the measured data, whilst in addition a viscoelastic ball model is developed to provide estimates of a ball's stiffness and damping coefficients. High-speed imaging tests are also completed to provide a more complete understanding of the impact mechanism. In addition, experimental modal analysis is used to determine the natural frequencies of the balls. The findings of this study allow differences in ball properties to be quantified, but it is not clear how such differences in dynamic properties are perceived.

Chapter 3 therefore presents the results of a series of interviews with elite tennis players to elicit their perceptions of 'feel' of a tennis ball. From the resulting transcripts, an inductive analysis is performed to structure the responses into
dimensions of 'feel' considered important to the players. The results of an online questionnaire are also presented that ascertain the relative importance of each of the 'feel' characteristics discovered in the perception study.

From the perception study, sound and feeling from impact are highlighted as two dimensions that are worthy of further investigation. Therefore Chapter 4 presents a literature survey on the human response to sound and vibration and the factors that may have a significant effect on the perception of 'feel' of a tennis ball.

Chapter 5 outlines the test methodologies for obtaining subjective and objective data for two separate experiments into sound and vibration. For the subjective data, suitable paired comparison questions are identified and a consistency test is developed for the analysis of the subjective responses. For the objective data, the test setups are outlined and instrumentation is developed, where appropriate, for the measurement of objective data in a realistic tennis environment.

Chapter 6 presents the results of the subjective data collected in the sound and vibration experiments. The results are statistically analysed to determine whether there are any significant differences between the subjective perceptions of tennis balls. Additionally, the results of the consistency tests are outlined for each player, with a further statistical analysis presented only for those players deemed reliable.

Chapter 7 outlines the analysis procedure and results for the objective data analysis. Suitable metrics are determined that may correlate with human perceptions of sound and vibration, and are determined for each ball used in the analysis.

Chapter 8 discusses the correlations found between the subjective data and the objective data collected in the sound, vibration and dynamic ball tests.

Chapter 9 describes opportunities for further work and Chapter 10 presents the conclusions of the research.
CHAPTER 2

Dynamic Properties of Tennis Balls

Tennis is a dynamic game in which the ball and player are constantly in motion, and where ball speeds can reach in excess of 150mph (Guinness World Records, 2005). To this end it is often impractical or unfeasible to analyse the dynamic properties of the ball in an actual playing scenario. Players often comment on the 'hardness' and 'softness' of the ball during impact and it is likely that these perceptions are related to such dynamic properties as the stiffness and damping of the ball. It is also likely that these properties are dependent on impact speed, hence adding complication to the overall assessment of 'feel' by the players.

In order to gain a more complete understanding of the ball's dynamic properties, a lab-based experiment was undertaken to analyse the impact of tennis balls against an instrumented force plate. Additional information was also provided through the use of a high-speed video (HSV) camera. The results obtained from the experiments, whilst not captured with synchronous players' perceptions, may give further indication of the dynamic 'feel' of the balls.

2.1. Dynamic testing of sports balls

The static properties of the tennis balls used in the study were outlined in Chapter 1 together with the results of the standard ITF ball tests. Whilst the static properties of tennis balls are rigidly specified by the rules of tennis, a wide variety of tennis balls with different physical properties are manufactured for the consumer. Although there are small variations permitted in mass, stiffness and size, it is likely that the large differences apparent during play are due to the fact that the regulations are not
specific regarding balls under actual play conditions (Cross, 1999). In addition, although the static tests are a quick and simple method, there is no evidence to suggest that they are a good predictor of how a ball will play at real game speeds.

Due to concerns that static properties may not predict how a ball will perform under play conditions, a number of studies have evaluated dynamic ball properties. A variety of methods have been used to obtain such properties including high-speed imaging (e.g. Cordingley, 2002), electrical switches (e.g. Johnson et al., 1973; Roberts et al., 2001b) and force plates (e.g. Cross, 1999; Haake et al., 2003). Properties that can be obtained directly from measurements include contact time, peak impact forces, coefficient of restitution and the coefficient of friction. Other properties such as stiffness and damping require a model to be fitted to the data that accurately represents the impact.

2.1.1. Coefficient of restitution
The majority of work completed on normal impacts concerns the coefficient of restitution (COR) of the ball. According to ITF regulations on rebound height, as outlined in Appendix A, the COR for a tennis ball must lie within bounds of 0.73 and 0.76 when dropped from a height of 100 inches. However, it has been found that the COR for sports balls does not remain constant with impact velocity. Daish (1976) states that the harder and, hence, faster a ball is hit, the more it compresses, resulting in greater energy loss. Due to the simplicity of evaluating the ball's dynamic properties through the measurement of the COR, the ITF has been addressing the possibility of applying limits to high speed COR values. Millar & Messner (2002) present a series of results from tests at 20m/s to 40m/s by firing balls using a compressed air powered ball canon against a rigid concrete block. The inbound and outbound ball speeds were recorded via light gates. The trend found for the dynamic COR against incoming ball speed is displayed in Figure 2.1. This trend has been supported by a number of other studies including Cross (1999, 2000), Cordingley (2002), Haake et al. (2003) and Rose et al. (2000) who, in addition, found a significant effect of the temperature on the dynamic COR with higher temperatures resulting in higher values of COR.
In addition, Bernstein (1977) describes a method by which the COR is determined indirectly from the sound made by the bouncing ball. A recording is made over several bounces of the ball and, using the time between impacts, an estimate of the COR can be made. Stensgaard & Laegsgaard (2001) present a revision of the method using a PC soundcard and software to analyse the sound file using steel balls dropped from a few centimetres.

2.1.2. Contact time

The contact time of a tennis ball has been investigated by numerous researchers for both rackets and rigid surfaces. It is not surprising that the contact time stated for the rigid surfaces is much less than those found on rackets, where the strings deform hence increasing the time of contact. The measurement of contact time on the strings of a racket is a more complicated affair, particularly when a player grips the racket, and, hence, the majority of studies have used a rigidly clamped racket in an experimental rig.

Haake et al. (2003) measured contact times on rigidly clamped rackets strung at two string tensions of 200N and 311N respectively. Contact times were slightly longer for more loosely strung rackets with values ranging from 4ms at higher-speeds to 6ms at lower impact speeds. Contact times were recorded through the use of a high-speed video camera and a slotted mirror that allowed the position on the strings to be monitored. The effect of the stringbed tension agrees with findings made by Brody & Knudson (1999). Other studies on the contact times for tennis ball impacts on rackets have been completed by Baker & Putman (1979) and Brody (1979), both reporting similar values of between 4-5ms. In addition, Cordingley (2002) assessed the differences between the contact times between balls and cores for both pressureless and pressurised types, through the use of a high-speed video camera. The balls were fired at a rigidly clamped racket. Significant differences were found between balls and cores with the latter having a longer contact time. In addition pressurised balls were found to have a shorter contact time than pressureless balls. Contact times of 3ms were reported at impact velocities approaching 40m/s for pressurised balls.

Force plates have also proved popular for the measurement of contact times of balls. Whilst rigid force plates are unlikely to provide an accurate representation of contact
times found on strings, they are useful for comparison of different balls. Such studies have been completed by Cross (1999), Dignall & Haake (2000) and Haake et al. (2003) all of whom report a decrease in contact time with increasing velocity, with typical values 1ms shorter than that found on rackets.

A further technique, which has been used to assess contact times in football and golf, is the use of an electrical switch. Studies have been completed by Johnson et al. (1973) in football and Roberts et al. (2001b) in golf who coated the balls in a metallic material, which acted as a switch. Whilst excellent measurement accuracy is attainable, with contact times in golf found to be around 450-490μs, the requirement to coat the balls in a metallic material, in order to act as the switch, would prove difficult on a tennis ball due to the cloth covering. The method would, however, be suitable for core impacts.

2.1.3. Coefficient of friction
When a ball impacts on a surface, the ball changes speed, it changes direction and it changes the rate at which it spins. The rate at which this happens is partly dependent on the coefficient of friction (COF) of the ball. To make an accurate measurement of the COF the ball must be sliding throughout the impact. At low angles of incidence this is likely to be the case but for larger angles of incidence the ball can ‘bite’, where the bottom of the ball comes to rest in the horizontal plane, or begins to roll, both of which result in inaccurate measurements of the COF.

Though the effects of the ball ‘biting’ have been investigated (Brody et al., 2002, p359) no study has been completed on the COF (μ) of different tennis balls. Values of μ have been found for a variety of tennis court surfaces ranging from 0.42 for smooth concrete to 0.8 for a clay court (Brody et al., 2002, p357).

In golf, Gobush (1996) measured the COF of golf balls through the use of two different methods, in order to compare the two. Balls were fired from an air gun to impact against a steel block set at an angle of 20 degrees to the launch direction. This was done to assure that sliding occurred between the ball and a club insert which was mounted on a force transducer. The first method used high-speed stroboscopic camera images to capture the position of seven markers on the golf balls. With
knowledge of the velocity components of the ball before and after impact, the COF can be determined through the use of Eq. 2.1 (Brody et al., 2002, p357) where $V_x$, $V_y$, and $V_z$ are the tangential and normal velocities before and after impact respectively. The impact angle is given by the value of $\theta$.

$$\frac{V_x}{V_y} = 1 - \mu \left(1 + \frac{V_y}{V_x} \right) \tan(\theta)$$

In a second method presented by Gobush (1996), a force plate was used to record the tangential and normal forces of the ball during impact. The time averaged normal and tangential force ratio was calculated in order to obtain the COF. The two methods were shown to compare well. The COF was shown to be higher in a wound balata ball due to the softness of the cover and to be dependent on the impact speed, with $\mu$ varying from 0.30 at a high impact speed to 0.38 at a low impact speed compared to 0.08 for a two piece ball at high speed and 0.16 at low speed. The measurement of the COF of a tennis ball is complicated by the construction of the ball cloth, which is comprised of a complex pattern of fibres. Studies have shown (Ajayi & Elder, 1994; Cordingley, 2002) that the COF is proportional to compression for fabrics and is highly dependent upon apparent contact area and sliding velocity.

2.1.4. Other dynamic tests

Whilst a number of studies have used the output of force plates in the estimation of contact time, a few studies have used the resulting force trace to assess the potential for injury. In two related studies in football, Levendusky et al. (1988) and Armstrong et al. (1988) used a force plate to find values of peak force, impulse (defined as the product of the average net force and the time interval), the duration (defined as the time period between 50% of the maximum peak force on the rise to 50% of the peak force on the downside of the pulse), and rise time (defined as the time period from 10% to 90% of the peak force). Impact speeds of 17-18m/s were obtained by dropping the balls from a predetermined height. Differences were found resulting from the variation in ball wetness, inflation pressure and the ball construction, with wetter, more highly inflated stitched footballs all providing higher peak forces and
shorter rise times. The authors concluded that the higher peak forces and shorter rise times increased the potential for injury.

Hendee et al. (1998), also looking at injury potential between two different types of baseball, reported values of peak impact force, impact duration and impulse. Shorter impact durations and higher peak forces were found for traditional baseballs and thus, the potential for injury was deemed greater.

2.2. The tennis ball impact

From studies of tennis ball impact force traces, as well as high-speed images of the impact, researchers have discussed how the ball behaves during impact. A typical force profile obtained by Cross (2000) is displayed in Figure 2.2. The impact is characterised by an initial sharp rise in force when the ball is compressed in the local proximity of the impact point. This is soon followed by a buckling of the hollow shell at the edge of the contact region (Cordingley, 2002). Cross (1999) goes on to suggest that a small normal force applied around the perimeter of the ball results in the contact area deforming into a relatively flat, circular disk and as the force increases the wall buckles as shown in Figure 2.3.

Evidence for this inversion of the contact region is presented by Cross (1999) through the use of a piezo-electric force plate showing the force output from directly under the inverted region to be zero during contact at ball speeds of 7m/s. This is supported by Ashcroft & Stronge (2002) who completed a series of compression tests on punctured and pressurised tennis balls, and present X-ray images of the inverted tennis ball. They found a pressurised tennis ball's contact region to invert at a deflection of 26mm whereas a punctured ball removed of all felt inverted at a deflection of just 12mm.

In an attempt to measure the deformation of the contact region during impact Cordingley (2002) used a laser vibrometer to measure the displacement of the contact region during impact. The balls were launched against a rigid surface with a window through which the laser vibrometer could measure the velocity of the contact region, which could subsequently be integrated to determine the displacement. The ball was covered in a retro-reflective material to aid the vibrometer signal. Results were taken
for pressurised and pressureless ball cores but no evidence could be found for any inversion of the contact region. It is also unclear what effect, if any, this inversion has on an actual ball impact.

2.2.1. Modelling of the tennis ball impact

The simplest method by which a tennis ball can be represented is that of a spring and damper placed in parallel. Such a configuration is known as the ‘Kelvin-Voigt’ bumper and describes dynamic strain and deformation that occur in a viscoelastic sample, under impulsive loading (Babitsky & Veprik, 1998). A representation of the model is shown in Figure 2.4. As shown in Figure 2.2, the tennis ball impact is characterised by an initial sharp increase in force and hence the viscoelastic model appears suitable for the application.

The equation of motion for such a system during the period of contact is given by:

\[ m\ddot{x} + c\dot{x} + kx = 0 \]  \hspace{1cm} \text{Eq. 2.2}

Given the initial conditions of \( x=0 \) at \( t=0 \), the solution to the equation is given by the well known solution:

\[ x = ae^{-bt}\sin \Omega t \]  \hspace{1cm} \text{Eq. 2.3}

Eq. 2.3 represents the displacement of the position of the centre of mass of the ball. Hence differentiating gives the velocity and acceleration respectively.

\[ \dot{x} = ae^{-bt}(\Omega \cos \Omega t - b \sin \Omega t) \]  \hspace{1cm} \text{Eq. 2.4}

\[ \ddot{x} = ae^{-bt}((b^2 - \Omega^2) \sin \Omega t - 2b\Omega \cos \Omega t) \]  \hspace{1cm} \text{Eq. 2.5}

Depending on the experimental data available for fitting, the above equations can be manipulated accordingly. Two such methods are presented by Dignall & Haake (2000) and Babitsky & Veprik (1998). Specifically for the study of tennis balls, Dignall & Haake (2000) used the COR of the ball and the contact time to find values.
of \( k \) and \( c \). This method was used in an experimental study by Haake et al. (2003) to determine the stiffness and damping for a number of types of tennis balls in an attempt to relate these properties to the 'feel' of the balls. Values of \( c \) and \( k \) found by Haake et al. (2003) are presented in Figure 2.5 for a variety of ball types. Using the values found for the unknown variables, the model force profile can be solved according to Eq. 2.5 as displayed in Figure 2.6, which displays both the raw data and model force profiles (Goodwill & Haake, 2004).

For calculation of model parameters the authors apply an additional condition that \( x=0 \) at \( t=T_c \) where \( T_c \) is the time of contact to give:

\[
\Omega = \frac{\pi}{T_c} \quad \text{Eq. 2.6}
\]

Equating the velocity to the incoming and outgoing velocities gives a further two boundary conditions:

\[
\dot{x}(0) = a\Omega = V_{in} \quad \text{Eq. 2.7a}
\]

\[
\dot{x}(T_c) = a\Omega e^{-bT_c} = V_{out} \quad \text{Eq. 2.7b}
\]

Hence the two constants \( a \) and \( b \) are given by:

\[
a = V_{in} \frac{T_c}{\pi} \quad \text{Eq. 2.8a}
\]

\[
b = \frac{1}{T_c} \ln \left( \frac{V_{out}}{V_{in}} \right) \quad \text{Eq. 2.8b}
\]

Hence both \( k \) and \( c \) can be found through the use of contact time, and the inbound and outbound velocities through the equations:
\[ k = \frac{\pi^2}{T_c^2} \quad \text{Eq. 2.9a} \]
\[ c = \left( \frac{2m}{T_c} \right) \ln \left( \frac{V_{\text{out}}}{V_{\text{in}}} \right) \quad \text{Eq. 2.9b} \]

Whilst the method by Dignall & Haake (2000) is simple to apply, measurements of contact time, inbound and outbound velocity are all required in order to calculate values of stiffness and damping. Babitsky & Veprik (1998) present a method by which the model can be fitted through analysis of the measured force only. They present acceleration data recorded from a viscoelastic impact of a steel bar against a plastic pad. The fit is completed through estimation of the contact time \((T_c)\) and time to peak acceleration \((T_p)\), both obtained directly from the measured data with the resulting ratio used to calculate the loss factor \((\zeta)\) according to Eq. 2.10.

\[
\frac{T_p}{T_c} = \left( \tan^{-1} \frac{2\zeta \sqrt{1 - \zeta^2}}{1 - 2\zeta^2} \right) / \left( \tan^{-1} \frac{4\zeta^2 - 1 - \zeta^2}{\zeta(3 - 4\zeta^2)} \right) \quad \text{Eq. 2.10} 
\]

The resulting value of \(\zeta\) can then be used in Eq. 2.11 to find the undamped natural frequency \((\omega)\).

\[
T_c = -\frac{1}{\omega\sqrt{1-\zeta^2}} \tan^{-1} \left( \frac{-2\zeta \sqrt{1 - \zeta^2}}{1 - 2\zeta^2} \right) \quad \text{Eq. 2.11} 
\]

The value of the constant \(b\) can then be found through the relationship between the loss factor and the undamped natural frequency where:

\[
b = \omega \zeta \quad \text{Eq. 2.12} 
\]

The remaining unknown parameters, \(a\) and \(\Omega\), can then be found through the use of Eq. 2.13a-b.
\[ \Omega = \sqrt{\omega^2 - b^2} \quad \text{Eq. 2.13a} \]

\[ a = \frac{\dot{x}_0}{\Omega} \quad \text{Eq. 2.13b} \]

In the presented example the initial velocity \( \dot{x}_0 \), is unknown and is estimated through the use of a least squares method (Babitsky & Veprik, 1998). These values are used to find a solution of Eq. 2.5 to produce the model acceleration profile. The excellent fit of the model is shown in Figure 2.7. The acceleration profile shown in Figure 2.7 displays very distinct start and end points, unlike those obtained from tennis ball impacts. This is due to the fact that a tennis ball is not a single-degree-of-freedom (SDOF) object and is non-linear. However, the SDOF viscoelastic model, due to its simplicity, is a useful place to begin in the analysis of the tennis ball impact.

### 2.3. Test equipment and protocol

It has been shown that it is possible to extract values for the stiffness and damping of a tennis ball through the use of force data captured at impact (Babitsky & Veprik, 1998). Therefore, a Kistler Type 9067 force transducer was used in order to analyse the dynamic properties of the tennis balls. The transducer consists of three layers of piezoelectric crystals which, when loaded, produce a small charge proportional to the change in loading. The crystal layers are housed within a solid casing, as shown in Figure 2.8. In order to measure normal and tangential dynamic forces it is necessary to preload the system. So the force transducer is mounted between two 15mm aluminium plates via a preloading bolt, which passes through the centre of the cell. As the piezoelectric crystals generate a charge only due to the change of an applied force, the constant load does not produce a signal. The preload is sufficient that the tangential forces are measured through the contact friction between the aluminium plates and the faces of the force transducer. The force plate assembly was attached to a large aluminium frame, which is capable of adjustment to obtain angles of impact from 0 to 90 degrees as can be seen in Figure 2.9.

In order to project the balls at high velocities at the force plate, a pneumatic ball canon was used. Air is supplied from the main compressor to a reservoir at 80 PSI,
which is connected to a pressure amplifier allowing air pressures up to 160 PSI to be generated. At this pressure, ball speeds in excess of 70m/s are possible. The air is triggered through a manually triggered valve through the breach, projecting the balls along a horizontal barrel. There are numerous barrels, which are interchangeable, allowing for all ball sizes to be investigated from ball cores to the Type III, oversize tennis balls. Balls are projected through a set of ballistic light gates, which enable the incident velocity to be recorded. The two photocells are placed 200mm apart and provide a measurement accuracy of ± 0.5m/s.

2.3.1. Calibration of equipment

2.3.1.1. Normal impacts

Through the addition of an additional external mass to the top of the force transducer, a correction is required to be applied due to the movement of this top plate during impact. Whilst the movement of the plate is small, the effect on the measured force can be significant. According to Kistler Instruments (2004), the dynamic behaviour of the force transducer is described by the motion of two masses with a spring, of zero mass and stiffness \( k_f \) and a zero mass damper, of damping coefficient \( b_f \), connected in parallel. The masses of the transducer in the model are discrete and as such divided into an internal upper mass \( m_u \) and an internal lower mass \( m_l \). The additional top and bottom plates of mass \( m_{ta} \) and \( m_{ba} \) respectively are assumed to be rigidly clamped to the force transducer. Hence the model of the force plate can be assumed to be that shown in Figure 2.10.

Equating forces at the top and bottom plates of the force plate gives:

Top plate: \[ F_{in} = m_t \ddot{x}_1 + \beta F_m \]  
Eq. 2.14a

Bottom plate: \[ m_b \ddot{z}_2 = \beta F_m - F_{out} \]  
Eq. 2.14b

where \( F_m \) is the measured force from the force transducer using the nominal calibration and:
\[ F_i = \beta F_m \]  

Eq. 2.15

where \( F_i \) is the true force applied to the spring/damper combination of the force transducer. The \( \beta \) term in the equation allows for correction to the calibration of the force transducer, which may be caused through the drift of the calibration of the instrument over time, or the effect of the preloading of the system.

Values of \( \ddot{z}_1 \) and \( \ddot{z}_2 \) are the acceleration values of the top and bottom additional masses respectively. The combined masses of the internal upper mass of the force transducer and additional upper mass and the internal lower mass of the force transducer and additional lower mass are given by \( m_i \) and \( m_b \) respectively.

When the plate is freely suspended \( F_{out}=0 \), but it will not be zero when in the experimental configuration, as displayed in Figure 2.9, and will remain unknown. Hence, in order to represent the output force of the transducer accurately, the acceleration of the front plate, the effective mass of the front plate \( (m_i) \) and \( \beta \) are all required.

To obtain values of \( m_i \) and \( \beta \), a series of calibration experiments were undertaken to ensure that all equipment was consistent with each other. As a starting point the accelerometers were checked against a calibrated Polytec OFV302 laser vibrometer. The accelerometers were individually mounted to the top of a shaker and the output of the accelerometer was compared to the output of the laser vibrometer pointed directly on the top of the accelerometer. Once confidence had been gained in the accelerometer calibrations, an impact hammer was calibrated so that a known force could be applied to the force plate and outputs compared. A freely suspended block of mass \( m \) with a calibrated accelerometer mounted onto it was struck with the impact hammer. The measured force from the impact hammer was then compared to the mass times acceleration of the block over the duration of the impact, to calibrate the impact hammer in the usual manner.

For the calibration of the force plate in the \( z \)-direction, the plate was mounted into its experimental configuration in the ball canon. Two calibrated accelerometers were
attached to the rear of the front plate which was struck by the impact hammer. Numerous measurements were recorded to find best-fit values for both \( m \) and \( \beta \). From the analysis, values of 1.5kg for \( m \) and 1.3 for \( \beta \) were found to best fit the data in terms of contact time and time to peak impact as shown in Figure 2.11. The value of 1.5kg for the mass of the front plate agrees closely with that obtained simply through estimation of the mass of the plate from its size and the density of the aluminium material, in addition to half the mass of the force transducer representing the internal upper mass of the transducer. It is clear that the effect of the correction is significant, in terms of the value of the absolute force measured, as well as the shape of the force trace, which affects both the time to peak impact and also the contact time. Whilst the values of force are very low compared to those obtained from high-speed tennis ball impacts, it is assumed that the relationships will remain linear or at least provide a reasonable approximation.

Figure 2.12 displays the raw output from the force plate, the averaged output from the two accelerometers, and the corrected data according to Eq. 2.14a for a Slazenger Wimbledon ball at 16m/s. There are a number of significant differences between the raw and corrected force plate measurements. Through the addition of the front plate acceleration the peak force has risen significantly. It is apparent from the corrected data that there is a much more clearly defined start of impact and initial rise in force. This initial sharp rise in force is a characteristic of a viscoelastic impact. Finally through the addition of the accelerometer data to correct for the movement of the front plate, some undesirable high frequency content has been included in the corrected force data. This motion, although undesirable, is genuine motion of the front plate, and not caused by the ringing of the accelerometers. This was confirmed through the use of a laser vibrometer to record the motion of the backside of the front plate, during a tennis ball impact, where the accelerometers had been attached. The resulting output of the vibrometer exactly matched that found from the accelerometers. This motion is likely caused by the front plate moving on the threads of the preload bolt and is a factor that must be taken into account in the analysis.

2.3.1.2. Oblique impacts

As for the normal impacts, the motion of the front plate must be accounted for in determining the true tangential force applied to the force plate. In a similar manner as
for the normal impacts, a calibrated impact hammer and accelerometers were used to impact the plate in the tangential direction, with the resulting outputs compared to determine a value for $\beta$ according to Eq. 2.16, where $\ddot{y}_1$ is the acceleration of the top plate in the tangential direction.

$$F_n = m_1\ddot{y}_1 + \beta F_n$$  \hspace{1cm} \text{Eq. 2.16}

From best fit measurements, a value of $\beta$ of 1.05 was found, together with the same value of 1.5kg for $m_1$.

### 2.3.2. Testing protocol

The six balls outlined in Chapter 1 were adopted for the experiment. Three balls of each ball type were used for the experiment. All balls used in the experiment were tested, and conformed to ITF regulations, as outlined in Appendix A. Three balls were used to provide an average value for each ball type. Ball speeds ranged from 14m/s to 66m/s, which was the working range of the canon and which encompass those speeds present at the top end of the male game that have not been previously considered. Incoming ball speeds were recorded through the light gates mounted inside the ball canon. Increments were made in 2m/s and hence 81 shots were recorded for each ball for each angle of impact. Through the use of the frame in the canon enclosure, the impact angle was adjusted from 90° to 15° in increments of 15°. Hence, for the six ball types and for all impact angles, over 3000 impacts were recorded.

For the tests, five accelerometers were mounted onto the plate. Two were positioned behind the front plate, to measure acceleration in the normal $z$-direction, a further two were positioned on the top of the front plate, to record acceleration in the tangential $y$-direction, with the remaining accelerometer positioned on the side of the front plate for any movement in the $x$-direction. For the normal impacts, only accelerometers mounted behind the front plate were used. The output from the accelerometers together with the three outputs from the force transducer were fed in two Brüel & Kjær NEXUSTM Type 2692 conditioning amplifiers. The data was acquired via a PC multi-channel data acquisition system at a sampling rate of 51.2 kHz, and 80ms of
data was acquired which resulted in a resolution of 12.5Hz. A pre-trigger was set so as to capture a few ms before the impact. The data was low pass filtered at 20kHz to prevent aliasing.

2.4. Analysis of normal impacts

2.4.1. Fitting the SDOF viscoelastic model

The two methods previously described by Dignall & Haake (2000) and Babitsky & Veprik (1998) both find values of $k$ and $c$ based on a single calculation taken from measured values of either COR, contact time or time to peak impact. Whilst both methods may produce reasonable estimates, it is likely that the value obtained is not the optimal fit to the data. In order to achieve this, the error between the model and the data should be minimized. As has been previously stated, the method by Dignall & Haake (2000) requires the incoming and outgoing ball speed to be recorded, but this was not completed in this study, and so this method is not suitable for obtaining the first estimate. Whilst the method by Babitsky & Veprik (1998) utilises known data from the force profile and initial velocity it involves numerous calculations, which can be achieved by alternative means.

In order to obtain the first estimate for the damping coefficient the value of the initial peak force was estimated from the experimental data. The deformation of the ball at this point, where there is assumed to be an instantaneous rise in force, is zero. Hence, Eq. 2.2 can be simplified to:

$$c = \frac{F(0)}{\dot{x}(0)} \quad \text{Eq. 2.17}$$

A first estimate of the ball stiffness was obtained by representing the force profile as a half-sine of period $2T_c$. The natural frequency of such a system being given by Eq. 2.18:

$$\omega = \sqrt{\frac{k}{m}} \quad \text{Eq. 2.18}$$
Therefore an estimate of the stiffness can be calculated through substitution of the contact time.

\[ k \approx m_0 \left( \frac{n}{T_c} \right)^2 \]  

Eq. 2.19

Clearly these values are crude estimates of the stiffness and damping. However, these values may be used as a first estimate in a numerical integration solution that iterates towards best-fit values.

Numerical integration solutions, rather than satisfying the governing differential equation (Eq. 2.2) at all time \( t \), only fit the equation at discrete time intervals \( \Delta t \) apart (Rao, 1995, p683). The solution found at time \( t_i \) is used to find the next solution at \( t_{i+1} \). One such numerical integration scheme is the finite difference method. By using Taylor’s series expansion, the solution of \( x_{i+1} \) can be expressed as a function of the previous solution \( x_i \) according to Eq. 2.20 (Rao, 1995, p684).

\[ x_{i+1} = x_i + \Delta t \dot{x}_i + \frac{\Delta t^2}{2} \ddot{x}_i \]  

Eq. 2.20

If it is assumed that the velocity is constant over each time increment, the velocity \( \dot{x}_i \) is simply approximated by the current displacement \( x_i \) and the previous solution \( x_{i-1} \) according to Eq. 2.21.

\[ \dot{x}_i = \frac{x_i - x_{i-1}}{\Delta t} \]  

Eq. 2.21

To obtain a solution for the force at time \( i \) the solution for \( x_{i+1} \) and \( x_i \) are required. In addition a correction is made to compensate for the movement of the force plate during impact. The values for the force plate displacement \( (y_i) \) and velocity \( (\dot{y}_i) \) at all points \( i \) are determined from the recorded acceleration measurements \( (\ddot{y}_i) \) and the use of simple kinematics using Eq. 2.22a-b. An average value of the acceleration is taken over three points.
\[
\dot{y}_i = \dot{y}_{i-1} + \left(\frac{\ddot{y}_{i-1} + \ddot{y}_i + \ddot{y}_{i+1}}{3}\Delta t\right)
\]

Eq. 2.22a

\[
y_i = y_{i-1} + \dot{y}_{i-1}\Delta t + \frac{1}{2}\left(\frac{\ddot{y}_{i-1} + \ddot{y}_i + \ddot{y}_{i+1}}{3}\Delta t^2\right)
\]

Eq. 2.22b

Hence the value of force at time \(i+1\) is given by Eq. 2.23.

\[
F_{i+1} = -k(x_{i+1} - y_{i+1}) - c\left(\frac{x_{i+1} - x_i}{\Delta t} - \dot{y}_{i+1}\right)
\]

Eq. 2.23

Hence the value of acceleration \(\ddot{x}_i\) can be found through knowledge of the force at time \(i\) according to Eq. 2.24.

\[
\ddot{x}_i = \frac{F_i}{m_b}.
\]

Eq. 2.24

Combining Eq. 2.20-2.24 yields the solution for \(x_{i+1}\).

\[
x_{i+1} = x_i + 2x_i - x_{i-1} + \frac{\Delta t^2 F_i}{2m_b}
\]

Eq. 2.25

Once the solution for \(x_{i+1}\) is known, the next value of \(F_{i+1}\) can be calculated through substitution into Eq. 2.23. The solution however is not self-starting and requires initial values of \(x_0\), \(x_i\), \(\ddot{x}_1\) and \(F_i\). At point \(i=1\) there is an instantaneous rise in force calculated through the use of Eq. 2.17 using the estimated value of \(c\) and \(\ddot{x}_1\), which is given by the initial incoming velocity. At this point it is assumed that the deformation of the centre of mass of the ball is zero and hence \(x_1 = 0\). The value of \(\ddot{x}_1\) is simply given by the ratio of \(F_1\) and the mass of the ball. The value of \(x_0\) may be calculated through the known values at \(i=1\) using Eq. 2.26 (Rao, 1995, p686).

\[
x_0 = x_1 - \Delta t\dddot{x}_1 + \frac{(\Delta t)^2}{2}\dddot{x}_1
\]

Eq. 2.26
Once the initial starting conditions are fed into the model, the force profile can then be reconstructed for all time \( i \). An error can then be defined as the least-square error between the model and the experimental data. Through varying the initial estimated values of \( k \) and \( c \) and comparing the resulting errors of the fit, the model converges on the ideal solution, defined as the minimum error between the model and the experimental data. Figures 2.13a-c display the model fit at three velocities comprising the range of the velocities used.

It is apparent from Figures 2.13a-c that the model under predicts the contact time of impact due to a tailing-off to the trace at the end of contact. Improvements to the SDOF model have been proposed by Goodwill & Haake (2004) that improve, in particular, the fit of the model at the end of contact. This model of Goodwill & Haake (2004) and other improvements to the SDOF model will be further discussed in Chapter 9.

2.4.2. Normal impact results

Using the model outlined above, values of stiffness and damping were calculated for each impact. In addition values of peak force and contact time were obtained directly from the force data. Figure 2.14 displays the results for the stiffness of the Tretorn ball, indicating the small level of scatter in the data. Figures 2.15a-d display the results of the analysis for all balls used. Due to the volume of data collected for each ball, a line of best fit was added to each ball’s data. The correlation coefficients for each line of best fit are also displayed on each figure.

It is apparent when analysing the stiffness data in Figure 2.15a that comparison between balls is complicated by the fact that the balls do not all follow the same trends, i.e. a ball that has a higher stiffness values at a lower speed does not necessarily have a higher stiffness value at a higher speed. In addition all trends are non-linear, with the highest values of correlation found through the use of a high-order polynomial to fit the data.

Whilst comparison between calculated values of stiffness for balls is difficult at lower speeds, above 30m/s two balls perform significantly differently. The pressureless Tretorn and oversize Precision have stiffness values significantly lower than those of
the remaining four pressurised balls, which display very similar values at higher velocities. This may highlight why there are negative comments pertaining to the pressureless balls, and to some extent the oversize ball, both of which perform closer to a punctured or depressurised ball at higher impact velocities. A punctured or depressurised ball would have low values of stiffness and a high damping coefficient for all velocities as shown in Haake et al. (2003).

Figure 2.16 displays values of stiffness and damping obtained in this study and also those found by Haake et al. (2003). Also included in the figure are values of static stiffness obtained from the ITF compression test (Appendix A), which require the ball to have a static stiffness of $12.6 \pm 1.7 \text{kN/m}$ (Cross, 2000). It is apparent that there is a very narrow range permitted for static values of stiffness, according to the ITF tests. Whilst the balls perform similarly at such static values the range of values of stiffness at high velocities are more than ten times the permitted static range. Values of stiffness in this study are significantly higher than those found by Haake et al. (2003), with a difference of approximately 20% for a pressurised ball at 40m/s. This indicates the differences in the method used for determining the stiffness, with this study producing a refined solution compared to a simple metric as obtained by Haake et al. (2003).

The damping values calculated for each ball are displayed in Figure 2.15b. The upper and lower limits, at all velocities above approximately 20m/s, are given by the Tretorn and Precision respectively. The higher damping coefficient of the Tretorn is likely due to the increased thickness of the core rubber required to obtain COR values at low speeds in order to conform to ITF testing limits. Conversely the damping coefficient of the Precision is due to the thinner rubber core thickness required as the Precision is some 6-8% larger than the other balls but is still required to have the same mass. Although values of damping coefficients obtained display strong trends for each ball, with little data scatter, it should be noted that the damping is hard to determine accurately as it is largely based on just a few values at the beginning of impact.

The values of peak force for all balls are displayed in Figure 2.15c. The peak force values are very similar for all balls below approximately 30m/s. Above 30m/s it is the
pressureless Tretorn that yields the highest peak force values. As shown in Hendee et al. (1998) for baseballs, there appears to be a linear trend between stiffness and peak force. Figure 2.17 displays this linear trend for the Fort Plus ball.

The contact time yielded directly from the force data is shown in Figure 2.14d. It is apparent that the contact times decrease with increasing velocity with contact times of up to 4ms present for low speed impacts down to approximately 1.5ms for high velocity impacts. It is difficult to draw any conclusion regarding the differences between balls, as no clear trends are apparent. In addition, as the contact time was estimated when the force profile became positive, the values at higher velocities are prone to some error due to the oscillations present in the data caused by the movement of the front plate.

As a player's perceptions of ball performance may be dependent on impact speed, three velocities were chosen that correspond to certain shot speeds as outlined in Chapter 1, and all parameters calculated accordingly at these velocities. The line of best fit was used to obtain the values at the chosen velocities. It was anticipated that these values would be used as a basis for correlation with subjective perceptions, to find whether any trends exist between the objective data and subjective perceptions.

The three speeds chosen for the analysis correspond to a typical serve (53.6m/s, 120mph), groundstroke (22.3m/s, 50mph) and volley (15.6m/s, 35mph) of an elite male player. The results of this analysis are outlined in Tables 2.1a-c.

<table>
<thead>
<tr>
<th></th>
<th>Stiffness (kN/m)</th>
<th>Damping (Nm/s)</th>
<th>Peak (N)</th>
<th>$T_c$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>138.8</td>
<td>65.6</td>
<td>4404.3</td>
<td>2.06</td>
</tr>
<tr>
<td>Fort Plus</td>
<td>146.8</td>
<td>69.0</td>
<td>4668.8</td>
<td>2.01</td>
</tr>
<tr>
<td>Precision</td>
<td>124.2</td>
<td>65.0</td>
<td>4384.3</td>
<td>1.86</td>
</tr>
<tr>
<td>Slazenger</td>
<td>141.9</td>
<td>71.5</td>
<td>4875.8</td>
<td>1.91</td>
</tr>
<tr>
<td>Tretorn</td>
<td>111.3</td>
<td>78.2</td>
<td>4926.7</td>
<td>1.88</td>
</tr>
<tr>
<td>Wilson</td>
<td>145.0</td>
<td>67.2</td>
<td>4291.2</td>
<td>2.39</td>
</tr>
</tbody>
</table>

Table 2.1a: Ball parameters for service impact speed 53.6m/s (120mph)
Stiffness | Damping | Peak | $T_c$
---|---|---|---
Absorber | 49.2 | 24.9 | 1015.1 | 3.61
Fort Plus | 58.3 | 25.1 | 1064.3 | 3.33
Precision | 49.2 | 22.2 | 1015.7 | 3.41
Slazenger | 54.3 | 24.9 | 1037.2 | 3.39
Tretorn | 50.2 | 27.0 | 1015.5 | 3.37
Wilson | 60.1 | 22.3 | 1123.1 | 3.48

Table 2.1b - Ball parameters for groundstroke impact speed 22.3 m/s (50mph)

Stiffness | Damping | Peak | $T_c$
---|---|---|---
Absorber | 39.6 | 15.3 | 667.9 | 4.05
Fort Plus | 48.5 | 15.4 | 745.1 | 3.64
Precision | 42.0 | 14.9 | 724.2 | 3.85
Slazenger | 46.4 | 14.8 | 762.5 | 3.78
Tretorn | 43.2 | 16.6 | 692.6 | 3.71
Wilson | 51.2 | 13.5 | 775.7 | 3.77

Table 2.1c - Ball parameters for volley impact speed 15.6 m/s (35mph)

For service values, the difference between the stiffest ball, the Fort Plus, and the least stiff ball, the Tretorn TXT, is 24% or 35.5kN/m. As the velocity is reduced, to groundstroke speeds the range decreases to 18% or 10.9kN/m. As the velocity is reduced further to volleying speeds the range increases to 23% or 11.6kN/m. Interestingly, for all parameters other than damping, the variation between balls at groundstroke speeds is at a minimum.

The largest difference in damping at service speeds between the Tretorn and the Precision is 14.6% or 11.2Nm/s. Values of peak force yield the smallest variation between balls with the largest differences being just 12.9% or 635N for balls at service speeds. Contact times are found to vary by 22.2%, between the Precision and the Wilson, with 0.53ms separating them at service speeds to approximately 10% at lower velocities.
The largest variations between balls are found for values of stiffness. Hence stiffness may play a greater role in the perception of the ball 'feel' than the other parameters. It is also apparent that the static properties obtained from the balls, as outlined in Chapter 1, bear little relevance to the dynamic properties at higher impact velocities. Hence it is not possible to predict the performance of the ball at realistic games speeds based on static data. It is also likely that the perception of a ball will be heavily influenced by the shot type. The results of this analysis, at realistic game speeds, will be used in an attempt to find any correlations with subjective data outlined in Chapter 6.

2.4.3. High speed video of normal impacts

As shown in Figure 2.13a-c, the SDOF model predicts shorter contact times than are suggested by the force traces. In order to verify the contact time and to gain a further understanding of the impact mechanism a Phantom high-speed video (HSV) camera was used to record the impact. The camera is capable of running at 100k frames a second but with limitations on image size. Therefore data was captured at 10 kHz, which for a typical impact of 2-5 ms provided between 20 and 50 image captures. The outputs from the force plate and accelerometers were also captured simultaneously with the camera, with both being triggered from light gates, so as to provide a synchronised force trace and set of images.

Figures 2.18a-h show a synchronised output at varying stages of the impact obtained from the HSV camera and force plate from time \( t_0 \) to \( t_6 \). Figure 2.18b displays the undeformed ball at time \( t_0 \), which represents the beginning of impact. Figure 2.18c shows the ball at time \( t_1 \) after the initial rise in force. It is apparent that the level of deformation is small and is confined to the area immediately surrounding the impact location. At time \( t_2 \), displayed in Figure 2.18d, the force trace is at its peak value. It is apparent that the ball has buckled and the front portion of the ball is still moving towards the plate. At time \( t_3 \), displayed in Figure 2.18e, the ball reaches its peak deflection, at a point that is significantly past the time of peak force. At this point the front of the ball comes to rest. Figure 2.18f displays the ball at time \( t_4 \) where there is a noticeable shift in the gradient of the force profile. At this point the ball starts to move away from the force plate but the back of the ball extends, thus prolonging the contact time of impact. This extension of the back section of the ball is clearly visible
in Figure 2.18g, at time $t_5$, which corresponds to the end of impact. This also confirms that the force profile can be used to accurately predict the contact time. It is apparent that the SDOF model underestimates the contact time due to the extension of the back portion of the ball. This cannot be accounted for in the SDOF model due to the assumption that the ball behaves as a single mass. Figure 2.18h displays the ball, at time $t_6$, after impact end once it has returned to its normal shape. The ball then oscillates at its natural frequency.

It is also of interest to compare the differences between impacts with pressureless and pressurised balls. Figure 2.19a-b show two extremely high-speed impacts at 65$m/s$ of a pressureless and pressurised ball respectively. It is apparent that the level of deformation is greater in the pressureless ball.

Finally, the HSV camera was used to look for any evidence of the inversion of the contact region as proposed by Cross (1999). A thick Perspex sheet was attached to an aluminium mounting with a central hole of 15cm diameter. The structure was mounted into the canon and balls were launched at the centre of the Perspex sheet such that the contact region could be viewed through the hole in the aluminium plate. A typical image found from the analysis is shown in Figure 2.20. Both pressureless and pressurised balls were used at a variety of speeds. It was anticipated that a darker region would form on the image if any inversion was present. However no evidence could be found of the inversion of the contact region through the use of this method.

2.5. Analysis of oblique impacts

The analysis to this point has only considered those impacts normal to the force plate. In addition data was collected for oblique impacts incorporating incoming angles of 75-15° in 15° increments as displayed in Figure 2.21. The study of the oblique impacts may yield additional information, particularly regarding the frictional elements of the impact.

As for the normal impacts, the data was corrected to allow for the movement of the front plate during impact. Figure 2.22 displays the raw tangential force plate output, the averaged accelerometer output and corrected tangential force plate output for an impact of a Slazenger ball at 25$m/s$ at an angle of 15°. The correction has an effect on
both the peak measured force, which is increased, and also the shape of the force profile.

Figure 2.23 displays the normal peak forces for all oblique angles recorded for a Tretorn ball. Normal impacts are not shown on the figure as they are very similar to the values found at an impact angle of 75°. As anticipated, the value of normal peak force decreases with a reduction in impact angle. It is apparent that if the normal component of the incoming velocity is used, the values of peak force are similar. Hence, the normal peak force can be assumed to be independent of impact angle and is only dependent on the component of normal velocity as suggested by Cordingley (2002). Plotting the normal component of velocity against peak force confirms this is the case, as can be seen in Figure 2.24, with all angles fitting the same trend. As the values of normal force are similar for the same component of normal velocity, for all impact angles, implies that all the energy losses in the ball, with the exception of friction, may be attributed to the normal component of the impact.

Values of tangential force are a direct measurement of the frictional force between the ball and surface. The measurements of tangential forces of a tennis ball are complicated by the construction of the tennis ball cloth which is typically made of a 'sateen' weave, with a complex warp and weft pattern. In addition to this, a finish is applied to the tennis ball called 'raising' that gives the ball its classic 'fluffy' appearance. The resulting effect is that the cloth will have directional properties that may have an effect on the measured frictional forces. In the experimental configuration the impact orientation cannot be fixed, and so there is likely to be scatter in the tangential data caused by the construction of the ball itself.

Tangential peak forces obtained for all angles and velocities for a Tretorn ball are presented in Figure 2.25. It is apparent that unlike normal peak forces, tangential peak forces are not solely dependent on either normal or tangential components of the velocity, both of which are displayed in Figure 2.26a-b.

To compare values of tangential peak force, impacts with the same normal velocity component are taken to provide a data set with constant normal load. In addition, if it is assumed that a constant normal load produces a similar deformation of the ball, and
hence apparent contact area, then the only variables between measurements are the
tangential velocity and the angle of incidence. In Figure 2.26a, trends may be fitted to
the data at each respective angle. It is apparent that similar trends exist between the
normal velocity component and tangential peak force, for angles of incidence of 15°,
30° and 45°, with values at 60° and 75° significantly lower.

Similarly, comparing values of tangential peak force at a constant tangential velocity
provides a data set where differences between tangential peak forces are due to the
angle of incidence and the normal velocity component, hence normal load and
apparent contact area. Again, it is possible to fit trends for each angle of incidence,
though it appears that not all trends are linear. The results suggest a high dependence
on normal load, with higher values of normal velocity components yielding larger
frictional forces at high angles of incidence.

It can therefore be concluded that normal load, apparent contact area, sliding velocity
and impact angle all have a bearing on the tangential or frictional force. In addition
the directional properties of the fabric, the wear of the ball and the impact orientation
are all likely to contribute. Due to the number of factors, making comparisons
between balls becomes increasingly difficult. It is anticipated that an increase in
frictional force is likely to be perceived by the players as an increased ability to apply
spin or ‘work’ to the ball, or that it ‘grips’ the court surface, though the perceptions
may vary according to any of the factors listed above.

The conventional means of measuring the friction of an object is to calculate its
dynamic coefficient of friction (COF) when the object is assumed to be sliding. The
ball is most likely to be sliding throughout impact at low angles of incidence
(Gobush, 1996). Figures 2.27a-b display HSV images of a Slazenger Wimbledon ball
at the start and end of an impact at 18m/s at an impact angle of 15°. A comparison of
the orientation of the ball at the start and end of impact indicates that, even at this
angle of incidence, the ball begins to roll before the end of impact.
The value of the kinetic COF ($\mu$) is simply given by the ratio of the tangential and normal force through the use of Eq. 2.27.

$$\mu = \frac{F_T}{F_N}$$  \hspace{1cm} \text{Eq. 2.27}

Figure 2.28 displays how the ratio $\frac{F_T}{F_N}$ varies for small time intervals throughout the impact of a Dunlop Fort Plus ball at 25m/s at an impact angle of 15°. Small time intervals were chosen that correspond to ten data points or 0.35ms in order to remove any variations in individual points caused by the oscillations in the data. It is apparent from Figure 2.28 that the value of $\mu$ starts high and then decreases. At the beginning of impact the forward velocity is at a maximum and the spin velocity is nominally zero. Friction then makes the ball start to rotate until it starts to roll. Hence the value of $\mu$ falls after the initial impact.

Error bars have been added to Figure 2.28 to account for the data scatter in the values of tangential and normal force corresponding to ±25 N variation in either of these values of force. It is clear that close to the end of impact where a ratio is being taken of two small numbers, the error in the measurement is large. Due to the errors in the measurement of the kinetic COF it is unreasonable to make a comparison between balls using this method, as differences between tennis ball cloths are likely to be small. In addition the results show that sliding is only likely at the beginning of impact and only at extreme angles of incidence.

2.6. Experimental modal analysis

In studying the dynamic properties of the tennis ball, additional information may be obtained through the study of the vibration characteristics via experimental modal analysis. Modal analysis has been used frequently in sports engineering with studies completed in golf (Varoto & McConnell, 1995; Wicks et al., 1998, 1999; Merkel & Blough, 1999; Hocknell et al., 1998), baseball (Tognarelli & Dunbar, 1994) cricket (Knowles et al., 1996) and tennis (Mohanty & Rixen, 2002).
The majority of these studies have been used to find the position of nodal points, and hence ‘sweet spots’, for which minimum vibration is produced for the various implements. In contrast Hocknell et al. (1998) used modal analysis to identify natural frequencies that were later linked to the sound produced at impact via the club head.

In terms of the study of the tennis ball, it is anticipated that although the mode shapes and nodal lines are of interest, they will not discriminate between balls, as all balls will vibrate in the same manner. However, the natural frequencies may provide information that may be linked to the sound of the ball at impact as well as its interaction with the racket. To this end each tennis ball’s natural frequencies were determined.

Each ball was attached to a shaker via means of a stinger, attached through the use of Araldite, and the ball was excited by a random input from the shaker. The experimental set-up can be seen in Figure 2.29. The entire assembly was supported to ensure that it was in a ‘free’ condition, with fishing line used to prevent excessive motion of the ball atop the stinger. In order to measure the response of the ball a Polytec laser vibrometer was used. Reflective tape was added to the ball to improve the signal to the vibrometer. The input force, measured via means of a force transducer, and the velocity of each ball point were analysed by a multi-channel computer based data acquisition system.

An example of the resulting frequency response function (FRF), provided by the ratio of the force and response, is displayed in Figure 2.30. Figure 2.30 clearly exhibits modes at approximately 205Hz and 430Hz. The mode at approximately 15Hz is the rigid body motion of the ball atop the stinger. If mode shapes were the primary concern of the study a large number of points would be required in order to completely represent the motion of the ball. However as only natural frequencies are required only a small number of points are required from which an average can be found. Hence five points were captured for each ball along a line of longitude and an average taken. Table 2.2 outlines the first natural frequencies for each of the balls used in the analysis. As the impact time is of the order of 5ms it is likely that that natural frequency of around 200Hz is the most important.
As expected, there is a clear and strong correlation with those static properties obtained in Chapter 1, as an estimate of the natural frequencies may be obtained directly from the measurement of static stiffness, with knowledge of the ball mass.

The shape of the first natural frequency is shown in Figure 2.31, obtained from Shannon & Axe (2002) who found the first natural frequency mode shape for an incompressible sphere, which is confirmed through the analysis of the HSV of a tennis ball impact. The second natural frequency, at approximately 430Hz, appears to be split into two, which may indicate a slight asymmetry of the ball core.

Whilst the natural frequencies, as for the other static tests, provide limited information regarding the dynamic impact characteristics at higher velocities, the natural frequencies will be used in further experiments relating to the sound and vibration of the ball.
CHAPTER 3

Elicitation of Players' Perceptions of 'Feel' in Tennis Ball Impacts

The previous chapter highlighted how differences in balls may be apparent in terms of their dynamic properties. However it is unclear how the players may perceive these differences. Therefore a study was completed to determine players' perceptions of significant ball characteristics, through a series of play tests and interviews.

3.1. Previous studies in the elicitation of perceptions in sports psychology

Methods of data collection and analysis are required that allow players' perceptions of the 'feel' of tennis balls to be evaluated. In the field of sports psychology, qualitative techniques have been used in order to obtain information for subsequent analysis. These qualitative methods permit the investigator to study the selected issues in greater detail. These studies have been completed on ice skaters (Scanlan et al., 1989a, 1989b), Olympic wrestlers (Gould et al., 1992a, 1992b), swimmers (Hanton & Jones, 1999) and golfers (Roberts et al., 2001a, 2002).

Scanlan et al. (1989a, 1989b) studied elite figure skaters and examined their sources of enjoyment and stress, and the roles that significant people in their lives played in these experiences. Interviews were conducted with 28 former elite figure skaters following an interview guide approach. The interviews were then transcribed and from these transcriptions an inductive content analysis was performed to structure the data.

Content analysis organises the raw data into interpretable and meaningful themes and categories and can be completed through either deductive or inductive analysis.
Deductive analysis involves using a predetermined set of themes and categories to organise the quotes, whereas inductive analysis allows the themes and categories to be determined from the quotes (Patton, 1990). The inductive analysis procedure begins by identifying emergent themes. These emergent themes are developed by clustering quotes around common threads. Clustering involves comparing and contrasting each quote with all other quotes and emergent themes to unite quotes with similar meaning and to separate quotes with different meanings. The inductive process then builds upon itself. The same compare and contrast procedures identify new, higher order themes. The analysis continues building up until it is not possible to locate further underlying uniformities to create a higher level theme (Scanlan et al., 1989a, 1989b).

Gould et al. (1992a, 1992b) completed a similar inductive content analysis to study a group of Olympic wrestlers regarding their mental preparation strategies and pre-competitive thoughts for their best and worst matches. Hanton & Jones (1999) also completed an inductive content analysis when they studied the cognitive skills and strategies underlying elite swimmers' interpretations of their pre-race thoughts and feelings.

Similar methods were used by Roberts et al. (2001a, 2002) who completed a study of 15 elite golfers to develop an understanding of the golfers' perceptions of the equipment they used. The authors used a semi-structured interview with open-ended questions to elicit the information from the golfers. The golfers were required to hit a number of shots with different club/ball combinations. The responses of the golfers were investigated further through the use of verbal probes, as well as identifying their ideal characteristics of a golf shot. From the results, an inductive analysis was performed and ten general dimensions of 'feel' were discovered. Roberts et al. (2001a, 2002) also developed a structured relationship model. This structured relationship model incorporated the general dimensions of 'feel' but also included inter-dimensional relationships that had not been previously discussed. An example of this is the effect of shaft length on club control, contributed to by both the 'feel' of the shaft length as well as the control the player had over the club.
The major steps used by the researchers (Scanlan et al., 1989a, 1989b; Gould et al., 1992a, 1992b; Hanton & Jones, 1999; Roberts et al., 2001a, 2002) involved in completing the analysis for all studies is as follows:

1. Transcripts of interviews are produced.
2. Transcripts are read and re-read until the investigator is totally familiar with the interviews.
3. Raw data themes are identified – quotes that capture the major ideas conveyed during the interview. These raw data themes are then checked for consistency through discussion with interviewers and an experienced third party, and by re-reading to ensure that all quotations make intuitive sense.
4. The raw data themes are listed combining the quotes for all the respondents.
5. An inductive content analysis is performed, to identify common themes from the lists of raw data themes. These raw data themes are grouped together to form second level themes. This grouping of themes continues until it is no longer possible, with the highest level themes identified being the general dimensions.
6. A deductive analysis on the raw data themes, higher order themes and general dimensions is completed through use of the original transcripts to verify that all themes and dimensions are represented.
7. Results are validated through consensus and triangulation to reduce bias. This involves the discussion of the emergent dimensions by the interviewers, as well as a third party experienced in qualitative data analysis, until agreement is reached for the analysis.

3.2 Interview technique

There are three main approaches to collecting qualitative data through open-ended interviews. Each approach serves a different purpose and has its own relative strengths and weaknesses as outlined by Patton (1990, p280-281).

1. The informal conversational interview
2. The general interview guide approach
3. The standardised open-ended interview
A summary of the methods as presented by Patton (1990) is given in Table 3.1, outlining the relative advantages and disadvantages of each of the three methods. The closed response style of interviewing is also shown for comparison.

<table>
<thead>
<tr>
<th>Type of Interview</th>
<th>Characteristics</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Informal Conversational Interview</td>
<td>Questions emerge from the immediate context and are asked in the natural course of things; there is no predetermination of question topics or wording.</td>
<td>Increases the salience and relevance of questions; interviews are built on and emerge from observations; the interview can be matched to individuals and circumstances.</td>
<td>Different information collected from different people with different questions. Less systematic and comprehensive if certain questions do not arise &quot;naturally&quot;. Data organisation and analysis can be quite difficult.</td>
</tr>
<tr>
<td>Interview Guide Approach</td>
<td>Topics and issues to be covered are specified in advance, in outline form; interviewer decides sequence and wording of questions in the course of the interview.</td>
<td>The outline increases the comprehensiveness of the data and makes data collection somewhat systematic for each respondent. Logical gaps in data can be anticipated and closed. Interviews remain fairly conversational and situational.</td>
<td>Important and salient topics may be inadvertently omitted. Interviewer flexibility in sequencing and wording questions can result in substantially different responses from different perspectives, thus reducing the comparability of responses.</td>
</tr>
<tr>
<td>Standardised open-ended interview</td>
<td>The exact wording and sequence of questions are determined in advance. All interviewees are asked the same basic questions in the same order. Questions are worded in a completely open-ended format.</td>
<td>Respondents answer the same questions, thus increasing compatibility of responses; data are complete for each person on the topics addressed in the interview. Reduces interview effects and bias when several interviewers are used. Facilitates organisation and analysis of the data.</td>
<td>Little flexibility in relating the interview to particular individuals and circumstances; standardised wording of questions may constrain and limit naturalness and relevance of questions and answers.</td>
</tr>
<tr>
<td>Closed, fixed response interview</td>
<td>Questions and response categories are determined in advance. Responses are fixed; respondent chooses from among these fixed responses.</td>
<td>Data analysis is simple; responses can be directly compared and easily aggregated; many questions can be asked in a short space of time.</td>
<td>Respondents must fit their experiences and feelings into the researcher’s categories; may be perceived as impersonal, irrelevant and mechanistic. Can distort what respondents really mean or experienced by so completely limiting their response choices.</td>
</tr>
</tbody>
</table>

Table 3.1: Interview style summary (from Patton (1990))
For the purpose of this study, an interview guide approach with the use of open-ended questions was deemed necessary. Open-ended questions have a number of advantages: they are flexible; they allow the interviewer to probe and go into more depth if necessary, or clear up any misunderstandings; they enable the interviewer to test the limits of the respondent's knowledge; they encourage co-operation and help establish rapport; and they allow the interviewer to make a truer assessment of what the respondent really believes. Open-ended questioning can also result in unexpected or unanticipated answers, which may suggest hitherto neglected relationships or hypotheses (Cohen & Manion, 1989).

3.3. Interview structure
The aim of the testing was to elicit responses from players during court play regarding their perceptions of tennis balls. In order to achieve this, a play condition must be stipulated that facilitates the players using their full range of tennis strokes. It is considered important that the whole range of shots must be used as the perception of the ball may vary for differing shot types. The test procedure must also comply with a number of other constraints such as the time available and the number of balls required for testing. In addition the interviews must be recorded and hence equipment was required to be developed to suit this purpose.

3.3.1. Testing scenario
After discussions with elite coaches a testing scenario was adopted where two players completed a standard 5-minute warm-up with each of the balls before the interviewers probed the player's perceptions. A 5-minute warm up is the standard length of time that a player has before a match, with the warm-up consisting of some loosening shots, both forehand and backhand, followed by coming to the net to hit volleys and 'smashes'. It is concluded by both players practising serves and returns. The advantages of this testing scenario were that two players could be evaluated at the same time, with two separate interviewers, and that each ball could be completed in 10-15 minutes thus restricting the length of test such that fatigue was not a concern. In addition, as the players were not competing, they would be more likely to focus on the ball and not on beating the opposition. The concern that 5 minutes might not be long enough for the players to gain an accurate assessment of the ball was not found to be a problem.
Other testing scenarios were developed and trialled through pilot testing. In the first a player completed a set shot pattern with each ball before giving their perceptions. However this scenario required a feeder, which was both time consuming and logistically difficult. A further test scenario was piloted where the players competed for two games with each of the balls. However the test took longer to complete with a lower number of shots completed per player, and their attention was drawn from the ball to concentrate on competition.

3.3.2. Equipment design

The interviews were recorded so that accurate transcripts of the data could be made. The equipment was required to be highly portable for transportation, and small enough and non-intrusive such that the players could wear the equipment whilst playing. To this end a wireless radio microphone system was used, which consisted of two lapel microphones, one worn by the player and the other by their interviewer. The lapel microphones fed into a small pocket radio transmitter, which transferred its signal to a base station, which was connected to a minidisk recorder. Through the use of an external sound mixer it was possible to record both the tennis player and interviewer on two separate tracks of the minidisk, set to record in stereo. The advantage of the separate tracks was to aid the transcriber in providing a full transcript when both player and interviewer were speaking at the same time. In order to prevent the equipment from dislodging during play, cases were provided that held the recording equipment snugly in the pocket. This whole system was duplicated for the second pairing of player and interviewer. However each system broadcast on separate radio frequencies to avoid interference. Figure 3.1 displays one of the systems used.

This system was found not to cause any inconvenience to the players. The players were not interviewed during play as it was difficult to communicate due to the distance between the player and the interviewer. In addition a digital video camera was used to record the play as well as making a backup of the audio data.

3.3.3. Participant selection

For the interviews, Lawn Tennis Association (LTA) Level 3 coaches were used because of their increased experience. Level 3 coaches have attained the highest
grade of coaching in the UK. Generally speaking, there are no rules for sample size in a qualitative inquiry. Sample size depends on what you want to know, the purpose of the inquiry, what is at stake, what will be useful, what will have credibility, and what can be done with available time and resource (Patton, 1990). There is also little consensus in the literature for the numbers required to perform accurate content analysis for elite sporting performers (Biddle, 2001). Numbers used have ranged from 75 elite athletes (Orlick & Partington, 1987) to ascertain their views on sports psychology consultants, to seven athletes (Rose & Jevne, 1993) used to gain insights into sports injuries. Scanlan et al. (1989a, 1989b) interviewed 26 athletes, Hanton & James (1999) 10 swimmers, Gould et al. (1992) 20 Olympic wrestlers and Roberts et al. (2001a, 2002) 15 elite golfers. For this study, the sample size was set at 16, which was a trade off between breadth and depth and inline with the majority of other work in the area. It was also found that, after this number had been interviewed, saturation was reached and no new data was emerging.

A pilot study was performed to ensure a sound procedure and enable minor adjustments to equipment and interview guide. In addition, ethical clearance was gained for the study.

Potential test players were approached and the tests arranged at their home indoor tennis centre. Where Level 3 coaches were not available, alternative players were found. In total, twelve of the test subjects were fully qualified Level 3 coaches, two of the subjects were full time tennis professionals and two were full time scholarship players. Table 3.2 displays the data for the subjects:

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Mean Age</th>
<th>σ Age</th>
<th>Mean Tennis Experience (yrs)</th>
<th>σ Experience (yrs)</th>
<th>Mean Years Qualified</th>
<th>σ Qualified (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3 Coaches</td>
<td>12</td>
<td>38.7</td>
<td>3.6</td>
<td>27.5</td>
<td>3.9</td>
<td>14.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Full Time Professionals</td>
<td>2</td>
<td>20</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Scholarship</td>
<td>2</td>
<td>18.5</td>
<td>0.7</td>
<td>8</td>
<td>0</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 3.2: Test subjects’ data
3.3.4. Interview guide

An interview guide was used to set the structure of the interview but not to lead the responses of the interviewer. The guide included key themes that were expected to be discussed, though topics were only discussed if first mentioned by the player. This list could be used by the interviewer as a checklist and as a reminder to probe the responses that had not emerged from earlier in the interview, if they later appeared. If the player did not mention any of the topics during the interview, these could be discussed after the interview was completed in order to gain some background information, but would not be included in the inductive analysis. The final section of the interview guide was used to obtain personal information from the players.

After some initial information regarding the nature of the test, the test was commenced by saying:

'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 all differing shots into your routine. After you have completed the warm-up I want you to describe your perceptions of feel for that ball.'

After the five minute warm-up, the interviewer would initiate conversation by asking an open-ended question, such as:

'How did that ball feel?'

A typical response:

'It was a hard ball, there was not much response in the ball when you hit it. It doesn't give much and feels a bit like a rock'

In order to clarify what each of the terms meant and to elaborate further on some points if necessary, elaboration probes were used:

'What do you mean by hard?'
‘What exactly do you mean by there was not much response in the ball?’

The interviews were completed in this way for the six balls of the test, as outlined in Chapter 1. A Latin square as found in Table 3.3 was used to set the order of the balls to ensure there were no order effects apparent. New balls were used for each test, and all conformed to ITF standards as outlined in Appendix A. No attempt was made to disguise the logo of the ball, after pilot tests found that the traditional blanking of the logo affected the ball’s visibility.

<table>
<thead>
<tr>
<th>Test No</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,9</td>
<td>Wilson</td>
<td>Tretom</td>
<td>Fort Plus</td>
<td>Absorber</td>
<td>Slazenger</td>
<td>Precision</td>
</tr>
<tr>
<td>2,10</td>
<td>Fort Plus</td>
<td>Wilson</td>
<td>Slazenger</td>
<td>Tretom</td>
<td>Precision</td>
<td>Absorber</td>
</tr>
<tr>
<td>3,11</td>
<td>Tretom</td>
<td>Absorber</td>
<td>Wilson</td>
<td>Precision</td>
<td>Fort Plus</td>
<td>Slazenger</td>
</tr>
<tr>
<td>4,12</td>
<td>Slazenger</td>
<td>Fort Plus</td>
<td>Precision</td>
<td>Wilson</td>
<td>Absorber</td>
<td>Tretom</td>
</tr>
<tr>
<td>5,13</td>
<td>Absorber</td>
<td>Precision</td>
<td>Tretom</td>
<td>Slazenger</td>
<td>Wilson</td>
<td>Fort Plus</td>
</tr>
<tr>
<td>6,14</td>
<td>Precision</td>
<td>Slazenger</td>
<td>Absorber</td>
<td>Fort Plus</td>
<td>Tretom</td>
<td>Wilson</td>
</tr>
<tr>
<td>7,15</td>
<td>Wilson</td>
<td>Tretom</td>
<td>Fort Plus</td>
<td>Absorber</td>
<td>Slazenger</td>
<td>Precision</td>
</tr>
<tr>
<td>8,16</td>
<td>Fort Plus</td>
<td>Wilson</td>
<td>Slazenger</td>
<td>Tretom</td>
<td>Precision</td>
<td>Absorber</td>
</tr>
</tbody>
</table>

Table 3.3: Ball order for tests

3.4. General dimensions of ‘feel’ of a tennis ball

Transcripts were produced for each interview, which resulted in over 500 pages of transcription data, and an inductive analysis was completed. Eight general dimensions for the ‘feel’ of a tennis ball emerged.

i. Ball sound
ii. Feeling from impact
iii. Bounce
iv. Control
v. Appearance
vi. Wear
vii. Ball flight
viii. Player’s psychology
The tree-structures for the dimensions are illustrated from Figures 3.2 to 3.9. Each
tree-structure illustrates how the analysis progressed from the initial quotes, examples
of which are provided in the left-hand column, through each different level of
clustering to the general dimension on the right-hand side.

3.4.1 Ball sound
The general dimension ‘ball sound’ as shown in Figure 3.2 contains all quotes in
reference to the impact sound. Five high-level sub-themes emerged from the analysis:

i. Sound descriptors
ii. Loudness of sound
iii. Difference in sound due to ball type
iv. Effect of sound
v. Sound due to location of impact

The term ‘sound descriptors’ was used to group all quotes that described the sound of
the ball. Such descriptors include ‘flat’, ‘hollow’ and ‘echo’.

“It sounded almost flat”
“I don’t know what makes up a ball, but I know you don’t really get
a solid ball but this sounds very hollow, you know as if there is just a
sort of thin layer covering and nothing else inside”

It may be possible to associate the described sounds of ‘pop’ and ‘dull’ with the
perceived pitch of sound and ‘echo’, ‘tinny’ and ‘pingy’ with the duration of the
sound.

“It’s a higher tone of sound; it’s more of a crisper pop”
“Yeah, the sound was dull there was no real pop to the sound. There
is quite a dull low tone on the bounce”

A number of the terms used to describe the sound of the ball were also used to
describe the feeling from impact. For example the term ‘tinny’ was used in both cases
and both were found to be highly undesirable.
"That ball you could really hear a tinny sound, it was horrible"
"It has got a tinny feel to it when you hit it. It's so kind of crisp it's almost metally, it has a metally feel to it"

The loudness of the impact sound was referred to by a number of players. All of the quotes pertaining to the loudness of the ball were with reference to the pressureless ball.

"The ball is much louder, it is like a bullet going off"

There were a number of other comments referring to the differences in sound between the pressurised and pressureless balls.

"The sound is different. I don't know what it is made of but it sounds different to a pressurised ball"

It was also found that ball sound could have a negative influence on the player by causing an additional distraction.

"It's just unpleasant you can't relax in that environment because of the noise"

In addition the ball sound may also provide feedback on the quality of shot. It was found by a number of players that a centre impact sounded different to an off-centre impact. However, this may also include accompanying frame and string noise, which was not distinguishable by the player.

"Because they are pressureless you have to hit it off the middle to feel a true hit. I mean if you don't hit it in the middle you can hear it in the ball, it's a different noise. It's perfect if you hit it off the middle but if you hit it slightly off-centre it is a different noise, it's a louder pop sort of noise, which makes it feel heavier"
The effect of the ball sound on the remainder of the ball dimensions will be discussed in section 3.5.1.

### 3.4.2 Feeling from impact

The general dimension ‘feeling from impact’, as displayed in Figures 3.3a-c, contains five high order sub-themes:

- i. Hardness of feel
- ii. Feel of ball behaviour
- iii. Feeling ball on racket
- iv. Weight of impact
- v. Feeling in arm

The theme ‘hardness of feel’ describes the perception of the hardness of the ball at impact, which can be comprised of either a ‘hard’ or ‘soft feel’. Specific terms were used to describe the perceptions for example the terms ‘tinny feel’, ‘crisp feel’, and ‘solid feel’ were used to describe a ‘harder feel’, whereas the terms ‘puddingy’ and ‘soft’ were used to describe a ‘softer feel’. It is clear that the players associated the ‘hardness of feel’ with the amount of deformation of the ball.

“I found them to be hard, very hard. I mean when you hit it, it is very solid it doesn’t give much”

“They definitely feel like the softest ball on the racket to be honest”

The high-order sub-theme ‘feeling of ball behaviour’ describes what the players perceive to be happening to the ball at impact. Players used the terms ‘lively’ and ‘dead’ to describe how the ball reacted off the racket face.

“This ball is livelier than the last ball it is really flying off the racket”

For a ‘lively feel’ the ball is perceived to have a very short contact time, with little deformation. In contrast a ball with a ‘dead feel’ is perceived to have a longer contact
time, with more deformation, which in turn the players perceive as an inability to generate pace in the ball.

"They are hard so they won't embed themselves in the racket face, they will fly off the racket straight away. These balls have a very high liveliness rating!"

"This ball you can feel when it grips into the string bed, you can sense that it is being pushed in, deforming in"

Players also commented on an ability to 'feel' the ball on the racket face.

"You felt as though you could feel the ball on the racket"

The perceived weight of impact was also found as a key factor. The players described the impact as either 'light' or 'heavy'.

"Some balls when you hit them it feels like a cannon ball it's a weightier kind of thing. I know it's probably the same weight in terms of actual weight as the other balls but it didn't have the same kind of feeling of heaviness, it seemed to leave the strings quite quickly"

It is clear that the ball type has an effect on the weight of impact. A pressureless ball is perceived to produce a 'heavier' impact than a pressurised ball.

"It's obviously a pressureless ball which automatically makes it feel heavier. It feels very heavy at the hit and you've got to work hard to strike it well"

It is also apparent that the perceived weight of impact is a complex sensation, with both 'hard' and 'soft' balls both being capable of producing a 'heavy' feel.
"The previous balls were very heavy but had a firm metallic feel to them where as this ball is even heavier but has a much softer feel to it"

In general, players prefer a light impact as these are perceived to be more comfortable and decrease the chance of injury. The weight of the impact was seen to cause vibration in the arm with higher levels of vibration attributed to a ‘heavy’ ball.

"It feels very heavy if you don’t strike it clean, I mean you can feel the vibration through your arm, I can already feel it in my elbow. OK you can feel that vibration’s there on your arm"

However the perception of high levels of vibration may also be attributed to the hardness of the ball ‘feel’.

"Very very hard on the strings on your body and on your arm"

Conversely a light ball was attributed to causing a low level of vibration in the arm.

"It was light which meant that it felt nice on the racket, not too much tension up your arm"

There was also an increased level of vibration for an impact that was not in the ‘sweet spot’.

"It feels really really heavy if you don’t strike it clean, I mean you can feel vibration through your arm, I can already feel it in my elbow”

"Well if you hit a harder ball you can feel the vibration in your arm slightly because it’s a bit harder especially if you miss-time it slightly"

3.4.3 Bounce
The general dimension ‘bounce’, as displayed in Figure 3.4a-b, is comprised of seven high order sub-themes:
There were a number of terms used by the players to describe a ball that had a high bounce. These include ‘springy’, ‘bouncy’ and ‘reactive’, which were grouped together under the theme ‘high bounce descriptors’.

"It generally felt quite light and springy"

"They were pretty bouncy off this court"

Similarly there were a number of terms used to describe a ball that had a low bounce. These included ‘skidding’, ‘dead’ and ‘low’.

"It didn’t bounce at all really, just skidded straight through"

The players directly correlated the hardness of the ball to its bounce characteristics, with a ‘harder’ ball being attributed to a higher and faster bounce due to the fact that it did not compress as much during impact with the surface.

"No it doesn’t deform as much as the other ball, which obviously you don’t want too much of but I felt that they were really hard so subsequently the ball, when it comes off the court you felt that it came off a lot quicker which meant you didn’t have as much time"

"This is a really hard ball so it bounced up high"

Conversely a ball perceived as ‘soft’ was considered to have a lower and slower bounce.
"It wasn’t as high bouncing, it was softer on the court"

"Painfully slow, it was soft and slow off the surface"

The perception of the height of the bounce was also affected by the perceived weight of the ball. A ‘lighter’ ball was perceived to bounce higher than a heavier ball.

"Those balls were pretty light and bouncy. I think that might have been due to the weight, they were pretty bouncy off the court"

"The feeling or sensation I get when it bounces, it is just a sort of steadier heavier bounce, which is lower"

The high-level sub-theme ‘characteristics of bounce’ groups together those quotes that describe the repeatability of the bounce. For example certain balls were found to bounce irregularly.

"A top-level player would use these once and chuck them I imagine because it’s losing its shape. I would have thought that it bounces imperfectly if tested"

Other characteristics include a true and predictable bounce, both of which were seen as favourable properties.

"Every single time you knew it was going to bounce, it was very predictable"

Other factors affecting the perceived bounce of the ball included the court surface and how a spinning ball interacts with it. The term ‘kicking up’ was used when a ball with topspin acted on the bounce. Some balls were seen to suit types of shot due to the way that the spin acted on the bounce.

"I would say that this is a slice ball. It hugs the floor a bit more on the slice"
The bounce is seen as a key component of the ball as the player must adapt their
game to suit the ball’s rebound properties.

“It’s a high bouncing ball but not very responsive to spin so if you
throw it high in the air it will bounce very high but if you hit heavy
topspin it doesn’t have any impact on the bounce, that’s a very low
bounce on a topspin flight path. So tactically you’d be better off
playing flat”

3.4.4 Control
The general dimension control as can be seen in Figure 3.5 contains those quotes
referring to the ability of the player to control the ball. Two high-order sub-themes
emerged from the inductive analysis.

i. Control of the ball off the racket face

ii. Ability to apply spin

A ball was generally perceived as either being ‘controllable’ or ‘uncontrollable’.
‘Controllable’ balls were perceived to have a larger deformation and hence longer
contact time that afforded the players extra time in which to control the ball on the
string bed. ‘Uncontrollable’ balls were perceived to ‘fly’ off the racket face, not
providing the player sufficient time to control the ball.

“You felt as though you could feel the ball on the racket enough time
to control it”

“Because it’s a bit harder you couldn’t control the ball as much
because it’s coming straight back off the strings quicker rather than
dehorning on the strings and you’ve got that split second to control
it”

The ability to apply spin or ‘work’ to the ball was seen as the major factor in being
able to control the flight and bounce of the ball. Certain balls were perceived to take
spin well, whereas it was difficult to apply spin to others. Again the link to the contact time of the ball was seen as a key factor.

“It feels as though you can put more spin on it because it’s a bit slower, it stays on the racket for a bit longer so you can put a bit more spin on it and really perhaps work the ball”

“They were less responsive to spin than the last balls. It was a real effort to get any work on the ball”

Other relationships that contribute to the control of the ball will be discussed in section 3.5.3.

3.4.5 Appearance
The general dimension ‘appearance’, as illustrated in Figure 3.6, contains five high-order sub-themes.

i. Size
ii. Visibility
iii. Size of ball ridges
iv. Sphericity of ball
v. Ball cloth

As a larger ball was used during the testing there were numerous comments about its size, most derogatory. Despite only having an increased diameter of 6-8% they were perceived as much larger by some players.

“How am I supposed to play with these beach balls??”

However in addition some balls were perceived to be smaller than a ‘standard’ ball, where the difference in size was much less pronounced.
"I think this ball is smaller than the other. To be honest I think the Wilson is smaller than the Dunlops, Slazengers and most balls to be honest"

The perceived visibility of the ball was also discussed, with the larger ball being described as easier to see due to its increased size, but also due to its speed through the air.

"... and big in the air, you could really see it off his racket"

The colour of the ball ridges, which are usually white, was also found to affect the visibility of the ball. Interestingly, the manufacturer of the ball with yellow ball seams promotes the ball as being more visible, due to the colour of its seams. However during the test one player commented that this actually made it less easy to pick out. Clearly the visibility of the ball is also dependent on the backdrop being used, which is likely to have a marked effect on the balls visibility in the air.

"There are different colour grooves, these are yellow whereas the others are white. I think it doesn't help in picking it out as easily against this backdrop"

Players also commented on the appearance of the cloth. In particular the density and quality of the felt used.

"High quality felt but loosely packed just looks like it is going to wear out quick"

3.4.6 Ball wear

The general dimension ‘ball wear’, as can be seen in Figure 3.7, contains those quotes that refer to how the ball ages. As the players were only playing for five minutes with each set of balls, wear is unlikely to have been an issue, so it is probable that the players are either referring to their own experience of the ball, or extrapolating using their experience of how the ball after five minutes of use will continue to wear. Five high order sub-themes were found during the analysis.
i. Ball pressure
ii. Ball fluffs up
iii. Ball loses cloth
iv. Effect of court on ball wear
v. Perceptions of durability of ball

Wear is clearly seen as a key issue for players.

“I mean tennis balls wear much quicker than they used to. A lot quicker, and in the tournaments that I would deal with in the juniors they often don’t get balls till the third set and I’m finding more and more that I’m having to put that in my coaching. You know this is the game you’re going to play with old balls and you want to come in a lot. So many times now post-match conversations with players the age of the balls is now becoming a massive factor”

The ball wears in terms of the deterioration of the cloth and also, for a pressurised ball, the pressure losses inside the ball. Therefore quotes regarding the pressure of the ball were either that the ball would maintain or lose its pressure. For the cloth it was found that the ball would either ‘fluff up’, where the cloth becomes loose and stands up, or the ball would shed its cloth, creating what some players referred to as a ‘skinhead’. Both forms of wearing were seen as undesirable.

“They did feel that if you played a match with them, they would fluff up quite a bit”

“This ball will lose all its fluff and become what we call a skinhead”

The court was also perceived to be a major factor on the rate of wear of a ball, particularly on the more abrasive surfaces.

“It’s going to wear out especially on clay or astro they are going to be eaten up by the courts a lot more”
It was found that the players were able to determine the likely durability from extrapolating the wear from their five minutes of play.

"Also a lot more wear on the ball, fluff is coming off so they are not going to last long"

Other players referred to their experience of using the balls.

"I've coached in a club that uses these balls, very popular for the members because a can will last them. Joe Punter, on an Astroturf court could use these for half a summer and they will be the same ball. It will stay because of the thickness it will stay, its character will remain and because of the poor condition of the felt it will just stay on"

As would be expected, the pressureless balls were seen to be more durable, due to their ability to hold their playing properties over time and as the cloth is generally seen as more durable.

The wear of the ball has a great affect on the playing properties of the ball, which may change substantially as the ball ages. This impact on the remaining general dimensions will be discussed in section 3.5.2.

3.4.7 Ball flight
The general dimension 'ball flight', as shown in Figure 3.8, is comprised of five high order sub-themes.

i. Speed of flight
ii. Adjustment to flight trajectory
iii. Weight through air
iv. Ability to control flight
v. Effect of ball compression
By far the most common quotes in this dimension referred to the speed of the ball through the air. This property greatly affects how the game is played, with players adjusting their games accordingly.

"Changing to that slower ball is almost like changing surfaces, you have to have a totally different game plan"

The speed of flight was referred to as ‘fast’, ‘slow’ or ‘average’. The speed of flight was seen as particularly important on the serve, where speed is a vital commodity. Adjustments to the service trajectory were required to be made where a ‘heavier’ or slower ball was used.

"On the serve because it's heavier I think and because naturally we hit down on our serves, so naturally because it's heavier and more gravity, I was really struggling to get it over the net. I would have to make a conscious change to hitting it up more on my serve than normal as literally just the mass of it was bringing it down"

The weight of the ball was seen to have an effect on the shape of the flight. A ‘heavier’ ball was perceived to stay ‘true’ to its flight, whereas a ‘lighter’ ball was perceived to have the tendency to ‘drift’ or ‘float’ during its flight.

It was also perceived that a lighter ball was more difficult to control through the air, due to it ‘flying’. This was seen as a problem in controlling distance, where spin was required to be applied to the ball in order to correct its flight path. On the contrary a slower or ‘softer’ ball was found to be much more difficult to over-hit due to the effort required to do so.

"The problem with a light ball is because they seem to fly very well it is very easy to over hit the ball. So if we take an extreme like the third ball which I think I described as puddingy (soft) that ball feels quite hard to over hit because you've got to do a lot with it if you like, because you've got to hit it hard to hit it out"
Some balls were also perceived to ‘move’ more in the air. This may be linked to the ability to apply spin to the ball.

"The top-spin serves that I hit they just didn't (move), I found with the Slazenger I could get the ball to move in the air quite a lot whereas these ones seem to not give me as much"

The effect of the ‘hardness’ of the ball on the ball flight was also discussed. It was perceived that a ‘softer’ ball travelled slower through the air. However this is more likely to be due to the inability of the player to generate pace with the ball than its aerodynamic properties.

3.4.8 Players’ psychology

The final dimension ‘players’ psychology’, which is illustrated in Figure 3.9, contains themes describing general feelings of the player as well as quotes describing other factors that can have a psychological effect on the player. Three high-order sub-themes were found during the analysis.

i. Positive responses
ii. Negative responses
iii. Effect of brand name

Positive responses included quotes relating to the enjoyment in using a particular ball, a perceived higher quality of ball and a ball that was perceived as comfortable to play with.

"Good ball, good ball. What I consider to be a high quality tournament ball"

"They feel really comfortable to play with. I wouldn’t have any concerns playing with these balls at all"

In contrast a number of negative responses emerged regarding the balls that included concerns over injury, not suited to style of play and a cheap quality of ball.
It is clear that the players have a number of preconceptions regarding the brand of ball gained from experience or reputation. This was clearly evident as some players would remark on a ball as soon as they picked it up.

"I mean I know what I am going to say about this one because I have previous experience of using these balls"

3.5 Structured relationship modelling
During the initial analysis, quotes were used to form the eight general dimensions. However this technique ignores any relationships between the dimensions that may be present. For example take the simple quote:

"They are a bit smaller than the last ball, and so they are a bit faster"

This quote describes the fact that the ball is smaller but also the relationship between the size of the ball and the speed of flight. In order to display these inter-dimensional relationships a ‘relationship map’ was created as outlined in Roberts et al. (2001, 2002). The ‘map’ is a visual method of displaying the dimensions discovered in the inductive analysis but also highlights the inter-dimensional relationships present, and is displayed in Figure 3.10. Each of the inter-dimensional relationships are further discussed in the following section.

3.5.1 Effect of impact sound
It has previously been discussed in section 3.4.1 that the players used the same vocabulary to describe the ‘feeling from impact’ as they did to describe the impact sound, therefore indicating that the impact sound may have a perceived effect on the ‘feeling from impact’ of the ball. In addition the impact sound was found to have an effect on the controllability of the ball. A ball that sounded ‘flat’ would encourage a player to strike it more firmly to compensate, which may lead to a loss of control.

"It sounded flat, so you felt like hitting it harder even though it went long and out of control"
3.5.2 Effect of ball wear

The perception that the ball changes significantly as it wears has a large effect on a number of dimensions. The most common perception was that when a ball 'fluffs up' this creates a larger and hence slower ball.

"The felt feels as though already the ball seems a lot bigger than it was compared to the other two"

"Quite fluffy round the sides, so it's a bit slower and it comes off the racket a bit slower"

"If it's a bit fluffy then it's not going to shoot and bounce and come through so quickly"

Conversely if a ball loses its cloth it will become a smaller and hence faster ball.

"This ball will lose all its fluff and that makes it what we call a skinhead and that just means it's going to be faster again"

"It's amazing, the more you use them the quicker they go"

It was also perceived that a ball's wear can be accelerated depending on its 'feeling from impact'. A softer, slower ball would tend to be struck with more effort thus increasing the wear on the ball.

"I mean just playing with balls like that they would just get so much hammer when you're playing with good players they would rip them to pieces really quickly"

Due to the perception that the balls become bigger and slower, they also are perceived to become 'heavier' as players are not able to generate as much pace with the ball.

"They did though feel that if you played a match with them they would fluff up quite a bit and they would get a bit heavier"
"These balls as they fluff up will just get heavier and heavier"

The perceived effort in hitting a worn ‘fluffy’ ball is also increased.

"These balls as they get quite fluffy and quite soft you have to put a lot of effort into them and the ball because it’s a bit bigger and perhaps fluffed up a bit it goes through the air not as quick and you end up having to put an awful lot of work into the ball to get any pace out of it which obviously you know by the end of the match can get quite tiring”

There can be an advantage in the ball wearing. A particularly ‘lively’ ball can become more playable after a small amount of wear, thus increasing the level of control of the ball.

"I know for certain that within an hour of playing with that first ball it would have just fluffed up enough to lose just a little bit of that flightiness but it would still feel light and that would make it much easier to control”

3.5.3 Factors affecting control

It has previously been discussed that the sound and wear of the ball can have an effect on the control of the ball. In addition to these the speed of the ball flight also affects the level of control, with a ‘faster’ ball providing less time for the player to prepare for the shot.

"You certainly had less time to prepare so I was mishitting and wasn’t quite timing it because the ball was going back and forth much quicker”

"It was travelling through the air much slower so you had more time to pick the ball out and prepare for your shot, so yeah it was easier to control”
A final factor that affects the ball's controllability is the bounce, with a steady, reliable bounce greatly aiding control.

"It didn't kick up at all it had a nice equal steady bounce which made it much easier to control"

3.5.4 Relationship between 'feeling from impact' and 'concerns over injury'

The relationship between the 'feeling from impact' and players' concerns over injury was introduced in section 3.4.2. It was generally perceived that a combination of the ball 'weight', 'hardness of feel', and 'feeling of ball behaviour' are all contributing factors to injury.

"I would say the weight of it for off-centre hits will cause vibration up the arm and also to get anything out of it you have to hit it by swinging faster. You were perceived as having to swing faster and over a period of time that feeling of having to swing faster will lead to problems"

3.6. Online questionnaire

The interview study highlights the characteristics that contribute to the overall 'feel' of a tennis ball. However the study gives each characteristic equal weighting, and does not identify whether one or all of the players introduced the theme. To investigate each dimension further, an online questionnaire was constructed that was sent to a wider population of tennis players to identify both their ideal 'feel' of a tennis ball and in addition the relative importance of each dimension.

An online questionnaire offers significant advantages over its traditional postal counterpart, which include the ability to contact a large number of participants quickly with minimal effort, coupled with the automatic compiling of the results in a database eliminating virtually all the processing time. The process also simplifies the role of the respondent.

The questionnaire was written in the coding languages of HTML and PHP, utilising a MySQL database to collect and compile the results. The questionnaire was then
placed on a domain and an email containing the hyperlink of the questionnaire was sent to approximately one hundred clubs throughout the United Kingdom with the request to forward it to additional club members. In total 165 responses were received.

The questionnaire was comprised of two separate parts as can be found in Appendix B. The first section of the questionnaire was used to obtain general information about the player's age and experience level. The second section of the questionnaire was designed to obtain the ideal 'feel' for each characteristic of interest and their relative importance.

For the questions relating to the ideal 'feel' and relative importance, a numbered scale was used, which would be familiar to those answering the questionnaire due to its widespread use, as well as providing scaled data directly. A major decision to make in defining an optimal numbered response scale is the number of points to use. The number of response options affects the scales' reliability and discriminability. Cohen & Cohen (1983) concluded that a minimum of three points is necessary whilst a maximum of nine points can be used effectively (Bass et al., 1974). Ten point (or more) scales tend to be employed less frequently as it is usually difficult to make distinctions finer than a 10-point scale requires, notwithstanding the fact that the larger the number of choices offered, the more complicated it is for respondents to utilise. Although a higher number of points may seem to gather more discriminating data, there is some debate as to whether respondents actually discriminate carefully enough to make these scales valuable. Overall, the extreme categories are found to be under-used. A choice was made to use a five-point scale, as it was felt that this would provide adequate discrimination for all ball factors included, without adding additional complexity to the questionnaire. An example question can be seen in Table 3.4. A further six questions of this type were included addressing all dimensions found during the interview analysis.

\[
\begin{array}{cccccc}
& & & & & \\
\circ & \circ & \circ & \circ & \circ \\
\text{Low in pitch} & & & & & \\
\end{array}
\]

Table 3.4: Example question of ideal 'feel' characteristic
In addition to each of the questions of ideal ‘feel’ the importance of each dimension was also addressed. Again a five-point numbered scale was used ranging from ‘not important’ to ‘very important’, as can be seen in Table 3.5. In addition a further seven questions were used to find the relative importance of additional ‘feel’ characteristics which can be found in Appendix B.

Table 3.5: Example question of dimension importance

3.6.1. Results for ideal ball ‘feel’

The results of 165 questionnaire responses were compiled to produce the following summary results. Graphs showing the ideal ‘feel’ responses can be found in Figure 3.11 a-g.

How hard would the ball feel? (See Figure 3.11a)

With a mean rating of 3.8 it is clear that players prefer a ‘harder’ ball. The responses were clustered around the upper end of the scale with only two respondents choosing a value below 3, thus indicating that a softer ball is a very undesirable property.

What would the weight of the ball be? (See Figure 3.11b)

It would appear that the ‘ideal’ weight of ball is a characteristic that varies between individuals. With a mean rating of 3.2 it is apparent that the majority of players prefer a slightly ‘heavy’ ball, although the spread of the data is much larger.

How quickly would you feel the ball to have left the racket face? (See Figure 3.11c)

With a mean rating of 3.9, it is clear that the players prefer the ball to leave the racket face quickly, which they perceive as a ‘livelier feel’. However, the mode is 4, which indicates that that there is a perceived loss of control if the ball is very ‘lively’.

How would the ball sound? (See Figures 3.11d-f)

Three questions were used to determine the ideal sound characteristics of the balls, those being pitch, loudness and duration. The mode of each of the categories is 3, indicating that the players prefer a sound that is not at the extreme ends of the scale.
The results indicate that the ideal sound should be slightly higher in pitch, and with a shorter duration, both indicative of a harder ball. It is apparent that more players would prefer a slightly louder sound, although again this seems to be down to individual preference, with more spread in the data.

*How much vibration would you feel? (See Figure 3.11g)*

It is apparent that players wish to feel a low amount of vibration in the shot with a mean rating of 2.1. Whilst the results are clustered around the lower three responses it is apparent that some players prefer to receive some feedback in terms of the vibration of the shot where as others prefer no vibration at all.

3.6.2. Results for relative importance of 'feel' characteristic

Table 3.6 lists the relative importance of each of the 'feel' characteristics rated in the questionnaire, ordered by their relative importance based on mean rating.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control of ball flight</td>
<td>4.78</td>
<td>0.44</td>
<td>5</td>
</tr>
<tr>
<td>Consistency of bounce</td>
<td>4.77</td>
<td>0.59</td>
<td>5</td>
</tr>
<tr>
<td>Control of ball on racket</td>
<td>4.76</td>
<td>0.60</td>
<td>5</td>
</tr>
<tr>
<td>Wear</td>
<td>4.56</td>
<td>0.57</td>
<td>5</td>
</tr>
<tr>
<td>Ability to apply spin</td>
<td>4.49</td>
<td>0.75</td>
<td>5</td>
</tr>
<tr>
<td>Hardness of feel</td>
<td>4.19</td>
<td>0.82</td>
<td>4</td>
</tr>
<tr>
<td>Level of vibration</td>
<td>4.17</td>
<td>0.91</td>
<td>5</td>
</tr>
<tr>
<td>Speed off racket face</td>
<td>4.13</td>
<td>0.75</td>
<td>4</td>
</tr>
<tr>
<td>Weight</td>
<td>4.11</td>
<td>0.80</td>
<td>4</td>
</tr>
<tr>
<td>Size</td>
<td>4.07</td>
<td>0.97</td>
<td>5</td>
</tr>
<tr>
<td>Appearance</td>
<td>3.78</td>
<td>0.99</td>
<td>4</td>
</tr>
<tr>
<td>Pitch of sound</td>
<td>2.91</td>
<td>1.11</td>
<td>3</td>
</tr>
<tr>
<td>Loudness of sound</td>
<td>2.88</td>
<td>1.14</td>
<td>3</td>
</tr>
<tr>
<td>Duration of ball sound</td>
<td>2.48</td>
<td>1.18</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.6: Relative importance of dimensions of 'feel'
It is apparent that the factors that have a direct influence on the player’s game are rated as having the highest importance, such as the ability to control the ball both in the air and on the racket face, as well as the consistency of the ball bounce.

The wear of the ball is also seen as a primary factor. This is likely due to the effect that worn balls have on other factors of the game, as well as the cost of replacing worn balls.

Factors which relate to the perceived 'feeling from impact' of the ball are rated lower, such as the level of vibration that the player experiences or the perceived 'weight' of the ball. All three sound characteristics are assigned the lowest importance. Whilst these factors may be perceived as being less important, it does not imply that these factors are unimportant, and all contribute to the overall perception of ball ‘feel’ as described previously in the Chapter.

3.7. Selection of characteristics for further study

The number of characteristics of ‘feel’ for a tennis ball that emerged was too great to enable each one to be studied in sufficient detail within the scope of this project.

The dimension ‘feeling from impact’ contains those perceptions that relate to the ball ‘feel’ at impact, and are likely to be related to the ball’s dynamic properties, which have previously been identified. This dimension also includes those quotes pertaining to the vibration level perceived by the player. Therefore a study of player’s perceptions of vibration at impact was completed. The results of the study will also be relevant in interpreting how the dynamic properties of tennis balls are perceived.

Sound is a particularly interesting dimension, and one that is intrinsically linked to the vibration of the ball, and also one that has an effect on the dimension ‘feeling from impact’. It is apparent from the questionnaire that this dimension is not rated as highly as others. However, it is clear from the interview study that the sound at impact can have a key effect on the player’s overall perception, particularly if the sound is seen as off-putting or distracting. It would be advantageous to identify which characteristics of the ball sound contribute to the perception of the sound at impact,
particularly with a view to highlighting those characteristics that may lead to a ball being rated negatively.

The two dimensions chosen allow test methodologies to be devised and analysis techniques to be developed that may then be further applied in the evaluation of the remainder of the dimensions and in other studies of this nature.
The physical quantities of sound and vibration may be simply defined. However, complex relationships exist between these physical quantities and the perceptual quantities of sound and vibration. The aim of this chapter is to understand the methods by which humans perceive sound and vibration and its specific influence to this study.

4.1. Human response to sound

The range over which the human auditory system can respond is huge. The absolute threshold provides the minimum detectable level of a sound in the absence of any other sounds. Such thresholds are found by determining the level required for an observer to detect the presence of a sinusoid at each of many different frequencies. In such tests, signals are generally kept to a relatively long duration of greater than 200ms. In Figure 4.1, the lowest curve, marked hearing threshold, is the threshold of audibility (ISO 226:2003). Figure 4.1 shows a clear dependence on frequency of the audibility of pure tones over the auditory range of approximately 20-20000Hz. The ear is most sensitive in the frequency range between 2 and 4kHz and becomes less sensitive for high and low frequencies.

For the threshold of audibility tests, the tones have a long duration, but it is well known that the threshold of audibility is dependent upon duration (Moore, 2003). Figure 4.2, reproduced in Yost (1994) from a study by Watson & Gengel (1969), shows the thresholds for various frequencies as a function of the duration of the signals. It is apparent from Figure 4.2. that for durations greater than approximately
250 to 500ms the threshold for various tones is similar. However as the tone’s duration is decreased the power of the tone must be increased for the subject to detect it. As shown in Figure 4.2 there is an additional effect of frequency, as outlined previously.

Two methods have been proposed to explain this dependence of the threshold of audibility on the duration of the signal. The first being that the ear acts simply as an integrator of the sound energy, such that a signal must have some critical amount of energy to be detected, and once the sound contains that amount of energy it is detectable (Yost, 1994). However this view has been superseded by the view that a long stimulus provides more chances to detect the stimulus through repeated sampling (Moore, 2003).

A further factor in the perception of sound is the effect of masking, that being the interaction of sounds. Masking can cause the threshold for one tone to be raised due to the presence of either another masking sound or where two sounds are presented close together in terms of time. Whilst the effect of masking is likely to be limited in this study, the effects and concepts of masking are incorporated into psychoacoustic metrics, which are defined later.

It is well known that tones that are close together in frequency cause a greater masking effect than those much further apart. To further evaluate this, Fletcher (1940) measured the threshold of a sinusoidal signal as a function of the bandwidth of a bandpass noise masker. The noise was centered at the signal frequency, and hence the total noise power increased as the bandwidth increased. Figure 4.3 displays the result of a similar study completed by Schooneveldt & Moore (1989) using a 2kHz signal. The threshold of the signal increases at first as the noise bandwidth increases, but then flattens off. Further increases in bandwidth do not change the signal threshold significantly. Fletcher (1940) called this value at which the signal threshold ceased to increase the ‘critical bandwidth’. In addition Zwicker (1957) found that the critical bands widened as the centre frequency was increased as illustrated in Figure 4.4 (Levine, 2000).
4.1.1. Loudness

Loudness is a subjective term describing the ear’s perception of the strength of the sound. Loudness is commonly measured in phons, with one phon defined in terms of a 1kHz pure tone, i.e. 40dB SPL for a 1kHz tone is equivalent to 40phon. The measurement of loudness in phon has two main drawbacks. One is that a subject tends to report that a 10phon increase in sound level sounds twice as loud. The other is that the correlation of phon with perceived loudness is not good for complex sounds. To correct for this, Stevens (1957) developed the sone unit for perceived loudness for which twice as many sones corresponds to a sound perceived twice as loud. One sone is arbitrarily defined as the level produced by a 1kHz tone of 40dB SPL. Figure 4.5 shows the relationship between perceived loudness in sones and the intensity level of a sound. It is apparent from Figure 4.5 that a doubling of perceived loudness corresponds to an increase of 10dB SPL and a ten-fold increase in acoustic energy.

Curves of equal loudness have been standardised in ISO 226:2003 that specify combinations of SPLs and frequencies of pure continuous tones, which are perceived as equally loud by human listeners, as shown in Figure 4.1. The curves tend to become flatter at higher intensities and, in addition, the rate of growth of loudness differs for tones of different frequency. For example, the absolute threshold for a 100Hz tone is about 24dB above that for a 1000Hz tone. However, for the 100 phon contour, the levels only differ by around 6dB between 100Hz and 1000Hz. Therefore, for loudness levels from the threshold to 100phons, the level of the 1000Hz tone must be increased by 98dB where as the 100Hz tone needs to be increased by only 80dB. Thus the rate of growth of loudness level with increasing level is greater for low frequencies than for middle frequencies.

The curves of equal loudness have been used in the design of sound level meters. The sound level meters do not sum the intensities at all different frequencies but rather weight the intensity at each frequency according to the shape of the equal loudness contour before doing the summation over frequency.

Figure 4.6 shows three commonly used weightings, the A, B and C respectively. The A-weighting is roughly based on the 30phon equal loudness contour. The B-
weighting is roughly based on the 70phon contour and the C-weighting roughly follows the 100phon contour (Moore, 2003). The A-weighting gives less emphasis to low frequencies. Consequently the A-weighting provides some benefits against wind noise and other low frequency noise from distant sources when making measurements, particularly outdoors (Fahy & Walker, 1998). However, it should not be assumed that the sound level meters give a direct estimate of the perceived loudness of a given sound, but they do allow rough judgements to be made between two complex sounds (Moore, 2003).

An important aspect of the loudness of a sound is the smallest change required for a listener to notice a difference in level. It has been reported that a change in level of 3dB is required to detect a difference in loudness (Hassall & Zaveri, 1979). However such a change in level is dependent on a number of factors including the frequency, level and duration, as well as how the sounds are presented.

The Weber fraction is often used to report the minimum perceivable change in a stimulus required for detection. The Weber fraction is given by $\frac{\Delta I}{I}$ where $\Delta I$ is the smallest change in intensity that is perceptible relative to the intensity of the reference tone, $I$. The results of a study by Riesz (1928), as reproduced in Coren (1999), of the frequency and intensity of a pure tone on the Weber fraction are shown in Figure 4.7. It is apparent from Figure 4.7 that the Weber fraction is increased for tones with a high or low frequency and for all tones at low SPLs. The increased Weber fraction is associated with a greater difference being required in order for the tone to be perceived. For moderate SPLs and mid frequencies it is apparent that changes in intensity as low as 10-20%, approximately 1dB, are capable of being detected in an ideal environment.

Whilst the majority of studies reported are of pure tones presented at a fixed frequency, a tennis impact is likely to be complex in frequency and so will be treated differently by the auditory system.
Given a complex sound of fixed energy of bandwidth $W$, if $W$ is less than the critical bandwidth for loudness then the loudness of the sound is almost independent of the bandwidth. The sound is judged to be about as loud as a pure tone or narrow band of noise of equal intensity lying at the centre frequency of the band. However, as the bandwidth increases beyond the critical band for loudness, the loudness of the complex sound begins to increase. Such an experiment from Zwicker et al. (1957), reproduced in Moore (2003), is displayed in Figure 4.8 where the critical band for loudness is approximately 250-300Hz for a centre frequency of 1420 Hz.

Two separate methods have been standardised in BS 4198 (1967) for calculating loudness based on the critical band theorem by Stevens and Zwicker. However, the Zwicker loudness method has come to be seen as the more useful method and is often used in sound quality instruments. The Zwicker method is designed to be used with one-third octave band measurements. The critical bands are approximated by one-third octave bands, but for low frequencies by two or more one-third octave bands summed together. Therefore, total loudness is the summation of specific loudness across critical bands with an additional factor for the effect of specific loudness on one band on adjacent bands. The Zwicker method for calculating loudness is complex as it involves plotting the critical band pressure levels on one of a series of ten charts and then measuring the area under the figure in order to derive the loudness calculated in sones. However, it is now possible to achieve this through the use of a software package.

4.1.2. Pitch

Pitch is a subjective quantity that is generally highly correlated with frequency but many other factors such as level and bandwidth can change the pitch of a waveform. The mel scale originally proposed by Stevens et al. (1937) is the most popular non-musical scale of pitch. A 1kHz tone at 40dB SPL is assigned a pitch of 1000 mels. As with the sone scale, the mel scale is proportional to the perceived change in pitch, i.e. a sound with perceived pitch twice as high as 1000 mels has a pitch of 2000 mels.

The pitch of a pure tone is primarily determined by its frequency but sound level also plays a small role. On average, the pitch of tones below about 2kHz decrease with increasing sound level, while the pitch of tones above about 4kHz increase with
increasing sound level. The pitch of tones in the middle frequency range remains relatively constant with increasing sound level. To obtain a difference, however, the intensity level has to change by 20dB or more and even then the change is relatively small (Gulick, 1971). In addition, whilst such a change may be perceivable for pure tones, increasing the intensity of complex sounds, such as a tennis ball impact, appears to have no effect (Gulick, 1971).

As with loudness, the perception of pitch is dependent on duration. The length of time for which a tone of a given frequency must last for a stable pitch to be determined is referred to as its critical duration. Tones shorter than this duration will be heard as a click regardless of frequency. It has been found that a tone with a frequency of less than 1000Hz must have a duration of 3 to 9 periods if the tone was to have a definite pitch. Above 1000Hz, this critical duration for the perception of tonality or pitch is 10msec regardless of the frequency of the tone (Yost, 1994). Even for tones that exceed the critical duration, the tonal quality increase up to about 25ms, above which further increases do not result in improved discrimination.

To investigate the change in pitch required to be detected, the Weber fraction has again been used. Figure 4.9 shows the results of a study by Weir et al. (1977) reproduced in Yost (1994) which displays the value of threshold \( \Delta f \) required to just discriminate from a given frequency \( f \). The value of the threshold increases as \( f \) increases above 1000Hz. However in the mid-frequency range the Weber fraction is approximately constant as can be seen in Figure 4.10 at 0.0015 (0.15%). This means that at low frequencies the threshold for detection of pitch can be as low as 1Hz.

Sharpness is a psychoacoustic metric that has been developed for the analysis of the frequency content of a sound signal. A value of sharpness provides an indication of the spectral balance between high and low frequencies (Zwicker & Fastl, 1999). The more high frequencies a signal contains, the higher the value of sharpness is. Values of sharpness are given in acum, where 1 acum corresponds to the perception of sharpness caused by band-pass noise at 1kHz with a level of 60dB and a bandwidth of 200Hz. The measurement of sharpness is generally independent of the sound level. Sharpness has a number of advantages over simply measuring the frequency content.
in that it takes into account the effect of critical bands. This metric has primarily been used for long duration sounds, and may not be suitable for impulsive sounds. However, a value of sharpness may be a good indicator as to the perceived pitch of the ball sound as well as a potential indicator for the pleasantness of the ball sound.

4.1.3. Studies of the sound at impact of sports equipment

It is clear that the perception of sound is complex, dependent on the frequency, intensity and duration of the sound. Nonetheless, a few studies have attempted to relate the sound generated at impact with the perceptions of players. These studies have primarily been completed in golf where ball sound has been linked to the perception of ‘feel’ of a shot (Hocknell et al. 1996; Kuwano, 1999; Roberts et al. 2001a, 2002) and also one that provides a relative ease of measurement as the ball impact location is fixed.

Hocknell et al. (1996) studied the sound at impact of a golf shot, and related the resultant frequency spectra to those obtained through analysis of the club’s natural frequencies. It was found that the peaks in the sound spectrum could be attributed to the natural frequencies of the various parts of the club head. It was also found that the location of impact resulted in a changed impact sound caused through the changes in amplitudes of excitation of different modes.

Roberts (2002) evaluated the correlation of golfers’ perceptions of the sound generated at impact to metrics of the sound collected via a sound level meter. The metrics included peak SPL, peak-to-peak SPL, duration, decay and weighted data according to the standard A and C-weightings. The strongest correlations were found between the subjective and objective data for the SPL over the first 50ms of impact. However, in addition, duration, decay and the centroid of the frequency spectrum all correlated strongly with the subjective data. The use of the sound weighting networks had little effect on the data. For the subjective data a ‘pleasant’ shot was one that had a ‘loud’, ‘explosive’, ‘crisp’ and ‘sharp’ sound. However, during the study, no use was made of the psychoacoustic parameters such as loudness or sharpness, which may be better correlated to the players’ perceptions.
Kuwano et al. (1999), also in the study of golf impacts, calculated the psychoacoustic metrics of loudness, sharpness, roughness and fluctuation strength. In addition, subjective data was collected in the form of paired comparisons. The strongest correlations were found between the difference in values of sharpness calculated at the impact point and 60ms after impact with the subjective quantities of ‘hardness’, ‘sharpness’, ‘powerfulness’, ‘vividness’ and also such sounds were found to be ‘refreshing’. Correlations were generally improved for loudness when the Zwicker method was used rather than peak SPL, or A-weighted SPL. The authors concluded that the Zwicker loudness level based on ISO 532B can be applied to the evaluation of loudness, and that the sharpness of the initial portion of the stimuli was a good measure of the ‘pleasantness’ of the impulsive sounds. They also concluded that the applicability of roughness and fluctuation strength to the evaluation of impulsive sounds was not clear.

Whilst direct sound measurements have not been made in tennis, a few studies have hypothesised that the sound of the impact may affect the perceptions of the players.

In evaluating the effect of string dampers on reducing vibration, Stroede et al. (1999) concluded that although the string dampers alone did not significantly reduce the racket vibrations, the effect of the damper was to reduce the sound produced by the strings, which had a significant psychological effect on the players.

In a study on the sensitivity of players to changes in string tension of a tennis racket, Bowyer & Cross (2003) found that the players made use of the sound to distinguish differences. When the sound was removed from impact the players’ abilities to distinguish between rackets dropped significantly.

From the result of the perception study, sound is clearly an attribute of the ball that has an effect on the players’ perception of ‘feel’. However, it appears that the majority of perceptions obtained refer to the negative aspects of a ball’s sound, which are seen as distracting. In general, pressureless balls are perceived to have such a distracting sound, which may partially lead to the general negative comments received about them. Therefore, it is of particular interest to distinguish the differences in sound between ball types. As the sound created at impact for a tennis
ball is complex in frequency, short in duration and will contain sound from the racket, the subsequent analysis of such sounds are likely to contain complex relationships to the players' perceptions. Perhaps of the most significant factors affecting the player's perception of the ball sound is the effect of duration. A tennis ball impact is of the order of 5ms which is likely to have a large bearing on the player's ability to accurately determine pitch and loudness.

4.2. Human response to vibration
Vibration in humans is sensed by various skin mechanoreceptors, which can be classified into two categories according to their adaptation and receptive properties. Slow adapting mechanoreceptors include Merkel disks and Ruffini endings, which respond to static pressure and slow changes in pressure on and beneath the surface, and are excited at low frequencies (<16Hz). Fast adapting mechanoreceptors, Meissner's corpuscles and Pacinian corpuscles, are primarily responsible for the detection of dynamic stimuli such as vibration (Griffin, 1990). Figure 4.11 displays the location of these mechanoreceptors in the skin.

It is widely believed that Meissner's corpuscles may be involved in sensations below about 20Hz to 40Hz while Pacinian corpuscles detect vibration in excess of this. Pacinian corpuscles are responsible for the frequency dependence of perception, showing greatest sensitivity to vibration in the region of 250Hz (Griffin, 1990). Meissner's corpuscles have a sensitivity to vibration that is much less dependent on frequency. In the range 20-40Hz either the Pacinian or the Meissner's corpuscle may be responsible for the perception of vibration depending on such factors as the contact area and pressure (Griffin, 1990).

The subjective response to hand-transmitted vibration has been used in several studies to obtain threshold values of vibration, contours of equivalent sensation and unpleasant or tolerance limits for vibratory stimuli at varying frequencies.

Threshold of perception tests typically involve a subject being excited through a vibration signal, the amplitude of which is reduced until the sensation produced by the vibration is just barely perceptible. Numerous tests have been reported in the literature, which vary in terms of the vibrating mechanism e.g. a handle (Reynolds &
Keith, 1977; Brisben et al., 1999) or a vibrating table (Miwa, 1967) and the location of the input of the vibration e.g. the palm of the hand (Miwa, 1967) or smaller locations on the hand such as the fleshy base of the thumb and the distal phalanx of the middle finger (Verillo 1963; Lamore & Keemink, 1988).

Roberts (2002) summarises these findings by combining the threshold perception curves obtained via the studies into a single figure, which is reproduced in Figure 4.12. There are a number of similarities in the curves, in that they have a characteristic shape, with two turning points, one between 10 and 40Hz and the other between 100-250Hz, indicating that the maximum sensitivity to vibration is somewhere between these values. The transition between 10-40Hz is caused by the transition from Meissner's corpuscles to Pacinian corpuscles. Differences between test results are likely to have been caused by variations in experimental configurations, which may include but are not limited to, the contact area, location of stimulus and force of contact. These curves were all obtained via excitation at discrete frequencies however it has been shown in Reynolds et al. (1977) that humans tend to be more sensitive to broadband vibration than discrete frequencies below around 100Hz.

From the studies, it is found that the thresholds of perception of hand-transmitted vibration are heavily dependent on a number of factors. These include vibration characteristics such as the frequency content, magnitude, duration and direction of vibration in addition to the contact area, contact force, grip configuration and contact point, as well as characteristics of the subjects such as age, pathology, subject attention, temperature and previous exposures to high levels of vibration. Acute exposure to hand-transmitted vibration can cause a temporary increase in vibrotactile thresholds due to a depression of the excitability of the skin mechanoreceptors. It is also found that vibrotactile thresholds are different in various locations on the body, which may be explained by the volume of receptors at these locations. It is also apparent from Brisben et al. (1999) that humans are capable of detecting RMS displacement levels of less than 1μm, and at the peak of human detection down to 0.01 μm.
Whilst absolute thresholds of vibration are widely reported, values of differential thresholds, i.e. the difference in value of two stimuli which is just sufficient for their difference to be detected, are not (Griffin, 1990). It is however hypothesised that differential thresholds will be affected by similar factors to absolute thresholds and be frequency, magnitude and direction dependent.

4.2.1. Vibration transmission to the hand and lower arm

The transmissibility of vibration from the hand into the arm has been investigated in a number of studies. It is not uncommon for measurements of vibration to be made at the hand, wrist, elbow and shoulder (e.g. Reynolds & Angevine, 1977; Hennig et al., 1992). In Reynolds & Angevine (1977), eight piezo-resistive accelerometers were attached at the fingers, wrist, elbow and shoulder in locations shown in Figure 4.13. Another piezo-resistive accelerometer was attached to a shaker and sensed the acceleration levels directed into the handle that was gripped by the subject. Two different grip strengths (9N and 35N) were investigated in two configurations, a finger grip where the handle was clasped only by the fingers and a palm grip where the handle was clasped with the fleshy part of the palm. This was completed in three directions of motion.

Figure 4.14 displays the transmissibility results obtained for Reynolds & Angevine (1977) for all three directions of motion. Not all locations are included in all three directions due to not being able to make measurements in the relevant directions. The results indicate that transmissibility through the finger to the middle phalanx is near unity up to around a frequency of around 100Hz indicating that the vibration was directed nearly unattenuated from the point of contact between the finger and the vibrating handle. Most of the vibration below 100Hz that was transmitted into the fingers was transmitted into the hand. However as the frequency increased the vibration tended to be localised to the fingers. The vibration amplitude at the wrist had decreased to around 10% the vibration amplitude incident upon the fingers at 100Hz and to 1% for vibration in the vertical direction and 0.1% for vibrations in the horizontal and axial directions at frequencies of 1000Hz.
It was also shown by Reynolds & Angevine (1977) that the orientation of the vibration has a dramatic effect on the transmissibility of vibration from the wrist to the elbow. Figure 4.15 displays vibration levels at the wrist and elbow for a vertical and horizontal vibration direction. In the horizontal direction, which in this case was perpendicular to the forearm, the transmissibility remains near unity whereas the vertical direction, normal to the forearm, appears to be dependent on frequency. This implies that longitudinal vibration is transmitted along a bone nearly unattenuated whilst transverse vibration is substantially attenuated as it travels along the bone.

Griffin (1982) and Macfarlane (1980), in assessing the influence of compliant materials on the transmission of vibration to the fingers and knuckle, found that transmissibility between finger pad and nail can be near unity up to almost 1000Hz with a moderate or high contact force. In addition, transmissibility to the knuckle of a hand gripping a handle tends to decrease below unity above about 100Hz.

As the natural frequency of a modern tennis racket is of the order of 200Hz, it is likely that the majority of the vibration will be confined to the fingers and hand of the players. It is also apparent that the strength and type of grip adopted will have a large effect on the transmissibility of the vibration into the hand/arm. Grip pressure has been measured by Bowyer (2003), who found variations during the stroke, ranging from an average pressure over the area of contact of 2psi before impact to 3.5psi immediately following contact. There was found to be an additional large variation in pressure for different locations on the hand with peak contact pressures of up to 22psi present.

4.2.2. Vibration studies in tennis

More specifically to tennis, various studies have recorded vibration amplitudes at the racket handle, knuckle, wrist and elbow (Fairley, 1985; Tomosue et al., 1991, 1994; Hennig et al., 1992; Kawazoe & Tomosue, 1993; Kawazoe et al., 1997, 2002; Naß et al., 1998; Maeda & Okauchi, 2002).

Fairley (1985) attached accelerometers to the racket handle and to the knuckle of a player whose racket was swung to hit a stationary ball. He concluded that all vibration frequencies up to 1000Hz were largely transmitted to the hand, which
conflicts to the studies presented in the previous section, where transmissibility to the knuckle tended to decrease above 100Hz.

Hennig et al. (1992), in studying the transfer of vibration from a tennis racket into the lower arm of a player, mounted two uniaxial miniature accelerometers to the skin above the ulnar head and the lateral epicondyle of the humerus, as displayed in the anatomical diagram of the human arm reproduced from Tortora (1995) in Figure 4.16. Twenty-three racket constructions were considered along with centre and off-centre impacts. Balls were fired at the racket by a ball machine to replicate the impact location accurately. Grip tightness was not recorded with players being instructed to hold the racket as they would do for a backhand stroke on a tennis court. Hennig et al. (1992) found the peak-to-peak acceleration at the wrist joint to be 4.5 times that at the elbow. In addition, off-centre impacts were found to produce peak-to-peak vibration values up to three times higher than central impacts. This has been confirmed by Tomosue et al. (1991) who showed that vibration amplitudes at the wrist joint and the racket handle in off-centre impacts to be 1.9-3.1 times and 1.3-1.6 times those of centre impacts.

In Hennig et al.’s (1992) study, large differences in arm vibration were found across subjects. Weak correlations were found between body weights and height with vibration levels being reduced in taller and heavier subjects. Strong correlations were found between resonance frequencies of the racket with the level of vibration in the arm, with stiffer rackets causing less vibration. This phenomenon is attributed to a smaller displacement of the racket head for a stiffer racket. The increased attenuation of the higher frequencies of vibration of the stiffer rackets, which may have played a role in the decreased level of vibration at the elbow, is not considered.

Various studies have investigated the effectiveness of damping materials on the transfer of vibrations from the racket to the hand and arm of the players. Tomosue et al. (1994) investigated the role of a string damper placed in the stringbed of the racket. Accelerometers were attached to the throat of the racket and to the Lister tubercle of the wrist as shown in Figure 4.16. Peak-to-peak acceleration values were reported from centre impacts only. Tomosue et al. (1994) found that vibration
amplitudes at the wrist were one tenth that at the racket handle. Whilst high frequency vibrations were only present at the handle, when comparing damped with undamped rackets, significant reductions were found in the measured vibration levels at the racket handle and wrist joint. There is however little agreement as to whether a device of such low mass can appreciably reduce the frame vibrations (Brody, 1989; Stroede et al., 1999). Tomosue et al. (1994) suggests that the reduction in string vibrations also reduces the amplitude of the frame vibrations.

Hatze (1992) evaluated the effectiveness of cushioning grip bands and discovered that grip bands had the effect of reducing the level of vibration transmission to a manusimulator, a device designed to replicate the human arm. In addition it was found that an increase in grip tightness corresponded to an increase in the level of vibration transmission. Maeda & Okauchi (2002) also demonstrated that the tightness of grip has an affect on the transmissibility of vibration from the racket to the hand. Accelerometers were attached to the hand and forearm, though no details are presented as to how this was achieved, or the precise locations. Incoming ball speeds of 6.3m/s were generated by dropping the balls from a height of 2m onto a horizontally held racket. No details are provided as to the strength of the two grips tested other than ‘rigid’ and ‘loose’.

Of all the studies of factors that may affect the transmissibility of vibration to the arm including grip strength, damping materials (grip bands, string dampers), racket head size, stiffness of the racket and impact speed only Kawazoe et al. (2002) and Knudson (2000) have considered the effect of the ball. Kawazoe et al. (2002) found no difference in vibration amplitudes from accelerometers mounted at the racket handle and wrist joint between a conventional ball and an oversize ball for a male completing a forehand ground stroke. In addition no differences were found between the two types of ball for measurements made at the racket handle, wrist and elbow for a player completing a service stroke. However, no consideration was made to the frequency content of the vibration, and it is not clear how subtle the comparisons were made during the study.

Knudson (2000), also investigating the effect of the larger ball, found larger accelerations present at the racket for the larger ball. Knudson speculates that the
players may have been compensating for the lower speed of the larger ball by imparting higher impact speeds, which would in turn lead to higher acceleration levels.

4.2.3. Tennis elbow

It is well known that exposure to high levels or repeated exposures to vibration introduce the potential for injury. Typically these concerns over injury arise from workers operating vibrating machinery, vibrating tools or vibrating work pieces. The injuries can be vascular disorders, bone and joint disorders, neurological disorders or muscular disorders (Griffin, 1990). Whilst tennis poses no risks for developing vascular disorders vibration has been suggested as one of the causes of tennis elbow (e.g. Hennig et al., 1992; Sessenger, 1995; Roussopoulos & Cooke, 2000).

Tennis elbow (lateral epicondylitis) is a term applied to elbow pain localised to the outside of the elbow. It has been found that lateral epicondylitis affects 40-50% of recreational players and medial epicondylitis about 10% (Roetert et al., 1995). Whilst not exclusive to tennis, tennis elbow is a major problem particularly for recreational players. A statistical study by Priest et al. (1980) on recreational tennis players revealed that 31% suffered from elbow pain at some time during their playing careers. This trend has been supported by Engel (1995) who claimed that 50% of regular tennis players will suffer pain in the elbow at least once in a lifetime. However the incidence of tennis elbow in elite tennis players is extremely low considering their frequency and intensity of play (Blackwell & Cole, 1994).

The pathology of the injury is agreed even though the precise causes are not. It is believed that microscopic tears occur in the tendon of the extensor carpi radialis brevis muscle and this results in inflammation and pain (Renstrom, 1994).

Roussopoulos and Cooke (2000), suggested the following potential causes for tennis elbow:
1. A single sharp impulsive stress and strain to the muscles, as from a badly hit ball.

2. An accumulation of 'normal' or slightly high stresses, from prolonged playing.

3. A sharp vibration in the loaded muscle, as from a badly hit ball.

4. An accumulation of many vibrations, each one not in itself dangerous.

5. Any combination of the above.

In addition, Segesser (1985) suggested that tennis racket oscillations in the range of 80-200 Hz are likely to contribute to the development of tennis elbow. Fairley (1985) also suggests that the vibration frequencies of up to 1000 Hz may be responsible for tennis elbow. These views are contradicted by Griffin (1990) who proposed that this problem might be caused through the repeated movements of a heavy implement i.e. the racket and not from the vibration itself.

There is a certain amount of anecdotal evidence in the tennis industry that equipment can help prevent tennis elbow through the reduction of vibrations (e.g. Kotze et al., 2002).

During the elicitation of player's perceptions of 'feel' of tennis balls numerous quotes were obtained linking the ball vibration with the potential for arm injuries. For example:

"I mean you can feel the vibration through your arm. I can already feel it in my elbow"

Due to the prevalence of vibration related injuries standards have been adopted in order to measure and limit vibration exposure. ISO 5349-1:2001 outlines best practise for the measurement of vibration and presents limits to ensure safe vibration exposure. In addition, in order to standardise vibration measurements a coordinate system is used which can be seen in Figure 4.17.
Whilst these standards typically concern injury to workers from vibrating machinery, ISO 5349-1:2001 provides a weighting curve to be applied to vibration measurements either as a digital filter or to one-third octave band measurements. This weighting curve is shown in Figure 4.18. The weighting concentrates on low frequency vibration with its peak in the 12.5Hz one-third octave band. The benefits of applying these frequency weightings to tennis appear limited, as the frequencies typically found in racket and ball experiments are of the order of 100-200Hz, which according to ISO 5349:2001 are very heavily weighted.
5.1. Subjective data collection

In order to measure the subjective responses of the players a data collection technique was required that allowed the subjective perceptions to be correlated with the objective data. In selecting a method to be used in this study a number of alternatives were considered.

Ranking the objects is by far the simplest and most straightforward method where judges are asked to rate the objects on one or more evaluation criteria. Typically the objects are presented sequentially and the ordering usually happens after all objects have been seen. Clearly the complexity of the ordering increases rapidly with the number of test objects. A disadvantage of the method is that it only gives an indication as to which objects are preferred to which but not the differences between them.

Rating scales are a common method for evaluating subjective data and have been used for the evaluation of sports equipment in tennis (e.g. Stroede et al., 1999), baseball (e.g. Noble & Walker, 1994) and golf (e.g. Roberts, 2002). In this method, objects are typically presented sequentially to the judge who assigns each one a numerical rating based on a criterion to be evaluated before moving onto the next object. The advantages of this method is that it is simple and quick to obtain the data and this data may be used for correlation with objective data.
However, numerical rating scales have many disadvantages and can be difficult for inexperienced, untrained judges to use successfully as they do not allow the judges to express their impressions in an easy and natural way (Otto et al., 2001). Inexperienced judges have little idea what a ‘3’ or an ‘8’ is, as the scale is missing a point of reference. In addition different judges will use the scales differently. Some will use the whole of the scale, whereas others may only use a small portion of the scale. One commonly used method to overcome this is to standardise the data to limit this effect (Giuliano & Ugo, 1992). This, however, introduces an additional level of complexity to the task. In addition, Borg (1998) argues that such scales do not permit any real measurements to be made as they give ratings that differ in rank order but not in distances.

One of the major criticisms of such rating scales is that the scales are derived from a fixed number of categories. However, people are capable of making much more accurate judgements of the relative magnitude of stimuli than such scales permit (Stevens, 1975). Hence, stimuli that are similar but that give rise to different magnitudes of sensation are often grouped into the same category simply because there aren’t enough categories to have one for each stimulus. Stevens (1957) popularised a procedure known as magnitude estimation in which subjects respond with numbers freely and according to their own feelings but in such a way that the relationship between the numbers corresponds to the relationships between the numbers. One drawback of this technique is that judges give widely different estimations. However, it is possible to overcome this through judge training or through standardisation techniques.

It has been found from studies of this nature that subjective perceptions do not scale linearly with the physical stimulus but rather are well described by a power function. For example, if the physical increase is 100% the perceptual one may be 200% or only 50%. Many studies of the perception of sound have been conducted by Stevens (1937, 1956) and Zwicker (Zwicker & Fastl, 1999), which highlight the complexities of the subjective rating of such physical stimuli.
Borg (1998) developed a series of scales, the most common of which being the rate of perceived exertion scale, which have the advantage that, unlike traditional numerical rating scales, the given ratings grow linearly with measures of physical exertion such as exercise intensity and heart rate.

Alternatively, in the method of paired comparisons, objects are presented in pairs and the judges are asked to make relative judgements of the objects. As only two objects are presented at one time it simplifies the judge's task, as they do not need to recall earlier objects. The method is particularly suitable where small differences are present.

Nunnally & Bernstein (1994) who studied the way that judgements are made concluded that:

"Whereas people are notoriously inaccurate when judging [absolutely], they are notoriously accurate in making comparative judgments."

Whilst it would appear that this method is suitable for all uses, it should be considered that the number of comparisons to be made increases rapidly with the number of objects present. For $t$ objects and $n$ judges the number of comparisons to be made is equal to $n \frac{t(t-1)}{2}$.

A test must therefore be designed with a small number of objects to be compared, or a non-balanced experiment must be used where not all comparisons are completed by each judge. An additional problem is that non-scaled data is produced and a complex algorithm must be used to obtain scaled data. A valuable feature of the method of paired comparisons is that it allows the inconsistencies in the judges' responses to be assessed.
5.2. Selection of subjective questions

The method of paired comparisons was deemed most suitable for the research, as it is likely that there will be very subtle differences between balls. In addition the method of paired comparisons allows the reliability of the judge to be analysed, which will be further discussed in section 5.3.

5.2.1. Sound subjective questions

Eight questions were chosen to analyse the players' perceptions of ball sound, which comprise factors found in the general dimension 'sound' and accompanying inter-dimensional relationship. As each of the questions was phrased for a paired comparison test, three options were presented for each of the questions. Where appropriate, descriptors were added to the questions to aid the players, which were found during the perception study.

Q: Compared to the first ball how did the second ball feel?
   i. More pleasant – Less pleasant – No noticeable difference
   ii. Softer – Harder – No noticeable difference
   iii. Lighter – Heavier – No noticeable difference

Q: Compared to the first ball how did the second ball sound?
   iv. Lower in pitch (duller/flatter) – Higher in pitch (crisper) – No noticeable difference
   v. Quieter – Louder – No noticeable difference
   vi. Shorter duration (pingy) – Longer duration (echo/hollow) – No noticeable difference

Q: Compared to the first ball how quickly did you perceive the ball coming off the racket face?
   vii. Slower (deader) – Quicker (livelier) – No noticeable difference

Q: Compared to the first ball how controllable was the second ball?
   viii. Less controllable – More controllable – No noticeable difference
5.2.2. Vibration subjective questions

Five questions were chosen to analyse the players' perceptions of vibration, which partially make up the dimension 'feeling from impact'. Due to the inter-dimensional relationship found between the dimensions of 'sound' and 'feeling from impact' there was some repetition of questioning from the sound experiment.

Q: Compared to the first ball how did the second ball feel?
   i. More pleasant – Less pleasant – No noticeable difference
   ii. Softer – Harder – No noticeable difference
   iii. Lighter – Heavier – No noticeable difference

Q: Compared to the first ball how much vibration did you feel with the second ball?
   iv. Less vibration – More vibration – No noticeable difference

Q: Compared to the first ball how quickly did you perceive the ball coming off the racket face?
   v. Slower (deader) – Quicker (livelier) – No noticeable difference

5.3. Reliability of judges

A valuable feature of the method of paired comparisons is that it allows the inconsistencies in the judges' responses to be assessed. The method of evaluating the reliability of a judge has typically been completed through the evaluation of triads. A triad is formed from the choices made between three objects, for example A, B & C. For the case where a judge is forced to choose between one or another object, there are eight possible outcomes of the triad \(2^3\), as each of the three comparisons (AB) (AC) and (BC) has two possible outcomes. Six of these outcomes are of the type:

\[ A \rightarrow B, A \rightarrow C, B \rightarrow C \]

where the arrow means 'is preferred to'. This indicates that one object has received two 'wins', the second object one 'win' and the third none.

The two remaining outcomes are of the form:
A \rightarrow B, B \rightarrow C, C \rightarrow A

and have been designated as circular triads by Kendall & Babington Smith (1940). A circular triad denotes an inconsistency on the part of the judge, and its simplest explanation is that the judge may be partially guessing when allotting preference. The judge may be guessing because the objects that are being compared are very similar, and hence they are unable to distinguish any difference.

It is possible to deduce the number of circular triads \((c)\) from a preference score matrix, an example of which is shown in Table 5.1, through the use of Eq. 5.1 developed by Kendall and Babington Smith (1940).

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Score (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>0</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1: Preference score matrix

\[
c = \frac{t}{24} (t^2 - 1) - \frac{1}{2} T
\]

where \(T = \sum (a_i - \bar{a})^2\) and \(\bar{a} = \frac{1}{t} \sum a_i = \frac{1}{2} (t - 1)\)

where \(t\) is the number of objects and \(a_i\) is score for each object in the preference matrix.

Kendall and Babington Smith (1940) went on to define the coefficient of consistence \(\Gamma\) as given by Eq. 5.2a-b.

\[
\Gamma = 1 - \frac{24c}{t(t^2 - 1)} \text{ for } t=\text{odd}
\]

Eq. 5.2a
If $\Gamma = 1$ then there are no inconsistencies present. As the number of inconsistencies increases so the value of $\Gamma$ approaches zero. It is possible to test $\Gamma$ for significance by using the chi-square’s distribution. By determining the probability of attaining the number of circular triads, a statistical judgement on the reliability of a judge can be made.

In the situation where three choices are offered to the judge, including one of no difference/preference, then the Kendall coefficient of consistency method outlined above is not appropriate.

The advantage of providing an option of no noticeable difference is that the judges are not forced to choose between factors that may be indistinguishable to them, and hence are not forced to guess repeatedly. In previous studies where a no-noticeable difference option has been presented, answers of no-noticeable difference were randomly assigned between the other two choices during the analysis of results (David, 1988). This is easy to complete but, when comparing consistency scores across judges and questions, the effect of randomly allotting preferences makes absolute comparison difficult and does not aid in the exclusion of judges for reliability.

For all comparisons between two objects, A and B, the judge has three possible alternatives. Assuming a question of preference is being asked, then the judge can either prefer A to B, prefer B to A, or have no preference between the two. Through introduction of a third object, C, it is clear that 27 distinct triads can be produced ($3^3$).

Whilst each of these triads are distinct, it is possible to group triads that display similar trends. In total seven triad groups can be determined. Each triad group is outlined in Table 5.2 together with an example.

In order to develop a measure of consistency, a scoring system is required to score each of the triads depending on the level of inconsistency shown. In the Kendall test
of consistency a circular triad, seen as complete inconsistency, is assigned a score of 1, whereas a true consistent triad is assigned a score of zero. In keeping with this method, a triad showing no inconsistency (Type 1) is assigned a score of 0 and a circular triad (Type 7) that of 1. Triad types 2 and 3, also show no sign of inconsistency because, if forced to make a definite choice rather than the no-noticeable difference option, the judge would always complete a true consistent triad. Triad types 4 and 5 are assigned a score of 0.25 because if the judge were forced to choose, they would have a probability of 0.25 of producing a circular triad, which would score 1. Similarly, Type 6 triads score 0.5 due to a probability of 0.5 of producing a circular triad.

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Example</th>
<th>Score</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>True consistent</td>
<td>C preferred to A</td>
<td>0</td>
<td>6/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C preferred to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>One clear winner</td>
<td>C preferred to A</td>
<td>0</td>
<td>3/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C preferred to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference A&amp;B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>One clear loser</td>
<td>C preferred to A</td>
<td>0</td>
<td>3/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference B&amp;C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Equality</td>
<td>No difference A&amp;C</td>
<td>0.25</td>
<td>1/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference A&amp;B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference B&amp;C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Two ties</td>
<td>No difference A&amp;C</td>
<td>0.25</td>
<td>6/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference A&amp;B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference B&amp;C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Inconsistency with one tie</td>
<td>A preferred to B</td>
<td>0.5</td>
<td>6/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>No difference B&amp;C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Circular triad</td>
<td>A preferred to B</td>
<td>1</td>
<td>2/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>B preferred to C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Triad definition

With a scoring system developed and all probabilities known, it is possible to extend the scenario to include a fourth object (D). There are now four possible triads, namely (ABC), (ABD), (ACD) and (BCD) contributing to the overall score. There are 729 ($3^6$) ways of producing these triads given the three response options of 'preferred', 'not preferred' or 'no-noticeable difference' and these are made up as follows. There
are 27 variations of the triad (ABC). For triad (ABD), one of the decisions (AB) has already been made hence there are 9 further possibilities. In triad (ACD), two of the choices have already been made, leaving just three further possible decisions to be made. Triad (BCD) has all its decisions made and hence no further outcomes are possible. Hence there are $27 \times 9 \times 3 = (3^5)$ possible outcomes. For each combination of four triads, the minimum inconsistency score attainable is 0 and the maximum inconsistency score possible is 2. This maximum score can be produced by two circular triads or by another combination of scoring elements. It is then possible, through the use of a computer script, to determine the probability of attaining each score, from 0 to 2, by analysing each of the scores of the possible 729 triads and hence determining the probability of a score arising randomly.

<table>
<thead>
<tr>
<th>Score</th>
<th>Number</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60</td>
<td>0.08230</td>
</tr>
<tr>
<td>0.25</td>
<td>56</td>
<td>0.07682</td>
</tr>
<tr>
<td>0.5</td>
<td>72</td>
<td>0.09877</td>
</tr>
<tr>
<td>0.75</td>
<td>96</td>
<td>0.13169</td>
</tr>
<tr>
<td>1</td>
<td>149</td>
<td>0.20439</td>
</tr>
<tr>
<td>1.25</td>
<td>96</td>
<td>0.13169</td>
</tr>
<tr>
<td>1.5</td>
<td>72</td>
<td>0.09877</td>
</tr>
<tr>
<td>1.75</td>
<td>56</td>
<td>0.07682</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
<td>0.08230</td>
</tr>
<tr>
<td>Totals</td>
<td>729</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.3 – Score probabilities for N=1

Table 5.3 shows the probability of attaining a certain score when answering one question with four objects. However, for the case where multiple questions are being asked, the model can be further developed.

If it is assumed that each of the questions is being answered independently, then it is possible to use the multinomial distribution to achieve this. The probability function for the distribution is given by Eq. 5.3.
\[
f(y_i | N, p_i) = \left\{ \frac{N!}{(y_0!)(y_{0.25}!)(y_{0.5}!)(y_{0.75}!)(y_i!)(y_{1.25}!)(y_{1.5}!)(y_{1.75}!)(y_2)!} \times \left( p_0^{y_0} \cdot p_{0.25}^{y_{0.25}} \cdot p_{0.5}^{y_{0.5}} \cdot p_{0.75}^{y_{0.75}} \cdot p_i^{y_i} \cdot p_{1.25}^{y_{1.25}} \cdot p_{1.5}^{y_{1.5}} \cdot p_{1.75}^{y_{1.75}} \cdot p_2^{y_2} \right) \right\}
\]

Eq. 5.3

Where \( N \) is the number of trials, or number of questions used, \( y_i \) is the number of occurrences of the result and \( p_i \) is the probability of the individual result given by Table 5.3.

Through the use of an additional computer script, it is possible to determine the score probabilities based on the number of questions from 1 to \( N \), with four objects. This method could be revised for five or more objects, but as the potential number of outcomes would be exceedingly large, processing time would be dramatically increased. As the experiments in this research used only four balls, no consideration was given to any higher number of objects.

Figure 5.1 displays the cumulative probability of achieving a certain consistency score, normalised for the number of questions, to fix the scale between 0 and 2 for any value of \( N \). It is apparent that the differences between the scores become smaller for increasing \( N \). Therefore there is a limited benefit in developing the model for larger values of \( N \) as values of \( N=7 \) will provide a close approximation. From analysis of Figure 5.1 there is a clear benefit in judging reliability over more than 1 question.

With knowledge of the cumulative probabilities of achieving less than or equal to a certain score, it is possible to make a judgement as to the reliability of a judge, by finding the cumulative probability of the judge achieving their score by chance. It is reasonable to assume that a player who is answering consistently is a reliable judge who should achieve a score with a low probability of having occurred by chance. Hence, by applying a cut-off, such as 5% or 10%, or cumulative probability values of 0.05 or 0.1, it is possible to exclude those judges who have answered inconsistently, for whatever reason.
5.4. Participant selection

Players for both sound and vibration tests were selected from the Loughborough University first and second tennis teams. Both male and female participants were selected. The LTA ratings of the players ranged from 1.9 to 2.1. The mean age of the players was 20.7 years, with a standard deviation of 2.1 years with average experience of 12 years of playing tennis, with a standard deviation of 2.6 years. All players were of at least county level standard and highly competent players. Sixteen players were used for both experiments, though due to equipment failure, only fifteen sound and fourteen successful vibration experiments were completed.

5.5. Ball selection

Four balls were chosen for both sound and vibration experiments. The four balls were chosen from the six balls used in the perception study in Chapter 2. The balls used were the Slazenger Wimbledon, the Tretorn TXT, the Dunlop Absorber and the Dunlop Precision. Only four of the six balls were chosen to limit the number of comparisons that would have to be completed. These four balls were chosen as they were expected to display the greatest difference in properties and so aid in the distinguishing of differences between balls. Details regarding the static and dynamic properties of the balls are presented in Chapter 1 and 2 respectively.

5.6. Measurement of objective data

Methods were required to capture objective data suitable for analysis and correlation with the subjective data for the sound and vibration experiments.

5.6.1. Sound data collection

A flat service shot, i.e. with little spin imparted, was chosen for the experiment. The amplitude of the sound is likely to be at a maximum at the serve due to the higher impact speed. In addition the use of the service shot required no additional equipment in order to launch the balls to the players, thus simplifying the experiment and removing any unwanted background noise that may be caused by a ball launcher. The disadvantage of this method is that the players were free to see the logo markings on the ball, and hence preconceptions of the players may become a factor.
A Bruel and Kjaer Type 2238 sound level meter was used for the experiment. The microphone was attached to an extension cable and placed at a height of 2.5m atop a tripod. The position of the tripod-mounted microphone relative to the player was adjusted depending on the position that the player chose to serve from. A position was chosen such that the microphone was as close to the impact position as possible but without the possibility of striking the equipment.

The sound generated at impact comprised external background noise, sound from the player, as well as the sound generated by the racket and ball. As the original player perceptions were obtained using indoor tennis courts and due to constraints of the weather, the sound tests were conducted indoors. Periods of the day were chosen when other activity in the tennis centre was at a minimum and the tests were temporarily suspended during periods of excessive background noise. Due to the size of the tennis centre and the impact sound duration, there were no reflections of the sound captured in the measurement other than that off the floor of the court.

The sound created by the racket will be comprised of discrete frequencies caused through the vibration of the racket and strings. Through knowledge of the frequencies of vibration of the racket they could in effect be subtracted from the overall sound frequency spectra, and those differences present, when the balls were varied, be attributed to the ball.

To this end a Bruel and Kjaer Type 4375V accelerometer was mounted to the throat of a Dunlop 200G racket, the details of which were presented in Chapter 1. The location was chosen for the ease of fixing the accelerometer to the racket frame and so that the cable could be run inside the grip to protect it. The accelerometer was attached via a stud mounting to the frame so that it could be changed quickly on court if broken. The set-up can be seen in Figure 5.2.

To further aid in the determination of racket noise, a modal analysis experiment was completed on the racket used in the analysis, to determine its natural frequencies. The natural frequencies of the racket should correlate strongly with the vibration measurements made on the racket frame. The results of this analysis are detailed in Table 5.4.
Mode | Frequency  
--- | ---  
1st Longitudinal | 127.19 Hz  
2nd Longitudinal | 327.97 Hz  
1st Torsional | 646.27 Hz  
3rd Longitudinal | 558.46 Hz  
1st String | 376.68 Hz  
2nd String | 962.32 Hz  

Table 5.4: Table of racket (Dunlop 200G) natural frequencies for sound experiment

The accelerometer was connected to a Brüel & Kjær NEXUSTM Type 2692 conditioning amplifier and the output from this together with the sound level meter were collected by a computer based, multi-channel, data acquisition system. The data were acquired at a sampling rate of 51.2kHz, and eighty milliseconds of data were captured resulting in a frequency resolution of 12.5Hz. The capture was pre-triggered to ensure the start of impact was collected, and a low pass filter of 20kHz was applied which is at the extreme of the auditory range, but primarily to prevent aliasing for the chosen sample rate.

The accelerometer cable was routed up the player's arm, through the use of wrist bands and clipped onto the back of their shirts to ensure it was held firmly out of the way before being routed to the charge amplifier. The players were asked to adopt a position on the service line so that they were confident that they would not strike the equipment, and the position was recorded so that they could adopt the same position for each serve.

Following a warm-up to familiarise themselves with the racket and cabling, the players were presented with twelve balls, incorporating six balls of each ball type being compared. The players were asked to serve the balls in whatever order they wished, thus removing any potential ordering effects, until they were confident that they could answer all the questions satisfactorily. Typically the players used all twelve balls before answering the questions.

Players were asked to identify any mishits for removal from the objective analysis. In addition in answering the perception questions, the players were informed only to consider the 'good' shots. The order of the comparisons of the balls is given by Table 5.5.
Table 5.5 - Latin square for ball sequence

5.6.2. Vibration data collection

In previous vibration studies in tennis, accelerometers were typically mounted directly on the frame of the racket. Whilst these may give a reasonable estimate of what the player is experiencing, they are at a different location to that where the racket is actually gripped. It is beneficial to measure directly at the grip interface. For such situations, ISO 5349-2:2002 recommends the use of an individually moulded adaptor which is moulded to the work surface on its lower face and to the palm of the hand on the upper surface with a space left for the accelerometer. Once the accelerometer is added, the adaptor can fit comfortably between the work surface and the hand.

As the adaptor is the sole point of contact between the player and the racket, the adaptor must not interfere with the grip, and not adversely affect the properties of the
racket. It is also important that the adaptor has a flat frequency response over the frequency range of interest. In order to achieve this the adaptor was produced of a lightweight and stiff nylon material.

Acceleration measurements were taken in two directions, X and Z, the directions of which are indicated in Figure 4.17. Acceleration values were not taken in the Y-direction, as it was anticipated that the other two directions would dominate, and in addition this measurement could not be made at the grip interface without the use of a tri-axial accelerometer.

Using a computer aided design package, a model of the adaptor was produced as can be seen in Figure 5.3. The adaptor was subsequently rapid prototyped to match the racket used. The bracket was attached to the racket handle on top of the grip and lightly held with adhesive tape. It was found during pilot testing that the adaptor caused minimal discomfort to the majority of players. There were some concerns for players with unconventional grips, and regarding the absorption of excessive sweat, but, due to the simple nature of the shot, these players were able to overcome such minor distractions. It is unlikely that the adaptors would be appropriate for a game-scenario, where a constantly changing grip is required.

Due to the larger amplitudes and a broader frequency range of vibration likely to be present at the grip, as well as the increased sensitivity at this location, the players’ perceptions are likely to be dominated by the vibration at the grip. Following the practise of previous studies into the vibration transmissibility to the hand/arm, measurements were also made at the second knuckle of the hand, the wrist (styloid process of the ulnar), and the elbow (lateral epicondyle) as detailed in Figure 4.16. In an ideal scenario, measurement of vibration would be made directly on the bone, but such a method is impractical. It has, however, been shown in Ziegert & Lewis (1979) that adequate measurements of the bone acceleration can be made through the measurements made from skin mounted accelerometers. In their study they compared a skin-mounted accelerometer output with an accelerometer connected directly to the bone by a needle through the soft tissue of the lower leg. The lower leg was then impacted at the heel and the resulting outputs analysed. They found that, for a low mass accelerometer (1.5g), the skin surface accelerometer showed a nearly identical
output to the bone acceleration. They demonstrated that the mass of the skin surface accelerometer had a large bearing on the validity of the result, reporting that the output of a 34g accelerometer mounted on the skin bore little resemblance to the bone acceleration. They concluded that the response of the larger mass accelerometer was affected by the resonance of the accelerometer on the soft tissue excited by the bone motion.

A number of methods have been proposed for attaching accelerometers to the surface of the skin. These include mounting with wax, elastic strapping, double-sided tape, medical and other adhesives. An ideal method for the test was one that was quick, caused minimal pain and discomfort, and was non-intrusive. Kitazaki & Griffin (1995), measuring resonance behaviour of the seated human body through vibration measurements at the spine, used thin stiff card attached to double sided tape to which they fixed an accelerometer. The double-sided tape was also used to bond the card to the skin of the subject. A similar set-up was chosen to that of Kitazaki & Griffin (1995) where a square of thin stiff card of dimensions 20mm by 20mm formed the base of the mounting to provide a larger surface area for the contact to the player’s skin, and a stable base for the accelerometer. Double-sided carpet tape was used to bond the accelerometer to the card. Surgical tape was placed on the player’s skin in order to prevent any skin reaction and for ease of removal from the skin. The double-sided carpet tape was also used to bond the bottom of the stiff card to the surgical tape on the player’s skin. The set-up is shown in Figure 5.4.

In a number of previous studies, a pre-load has been applied to the accelerometer through the use of elastic strapping or other similar materials. A pre-load is generally applied to improve the contact between the accelerometer and the bone and to prevent any movement of the accelerometer. However, according to Kitazaki and Griffin (1995) the additional materials required to preload accelerometers may result in additional resonant systems. In the case of Kitazaki and Griffin (1995) where pre-loading was not used because of the measurement location on the spine, a data correction method was devised to eliminate any relative movement of the skin compared to the bone. A single degree-of-freedom linear model for the local tissue-accelerometer system was assumed and they present a correction frequency response function through the estimation of the natural frequency and damping ratio.
In pilot player testing of the accelerometer mounting, no change to the signal was found through the application of an elastic strapping, which was, however, causing additional difficulties in the application of the accelerometers to the players. With difficult measurement locations on the knuckle, in particular, it was found that there was no benefit to applying the strapping as there was a potential to correct for any local skin movement, if applicable, at a later opportunity in the analysis.

In order to check the influence of the mounting, an experiment was completed whereby calibrated accelerometers were mounted back-to-back in two configurations. In the first, the accelerometers were superglued together and hence securely bonded. In the second, the tape and card from the experiment were used to simulate the mounting onto the back of the accelerometer. The transfer function of the result is shown in Figure 5.5. It is apparent from the results that for the frequency range of interest the mounting provides an excellent representation of the signal and only starts to drift off by a small factor above 250Hz.

To measure the vibration at the grip of the racket and on the hand/arm, two types of miniature accelerometers were used. Two Endevco Type 2222C accelerometers, each of mass 0.5g, with an operating frequency range of between 0.5-10 000Hz, were attached to the grip mounted adaptor. The accelerometer’s flat profile is ideal for placement between the hand and the racket of the player with minimal discomfort. Another Endevco type 2222C accelerometer was attached to the knuckle of the player. Two Bruel and Kjaer Type 4375V accelerometers, each of mass 2.4g, with an operating frequency range of 0.1-16 500Hz were attached to the wrist and elbow of the players. The accelerometers fed into two Brüel & Kjaer NEXUSTM Type 2692 conditioning amplifiers. A computer based, multi-channel, data acquisition system was used to capture the data. The data was acquired at a sampling rate of 51.2kHz, and eighty milliseconds of data was acquired which resulted in a resolution of 12.5Hz. A pre-trigger was set so as to capture a few ms before the impact. The data had a low pass filter of 20kHz. Whilst frequencies over a few hundred Hz are not likely to be of interest for the vibration study, a value was chosen to prevent aliasing for the chosen sampling rate.
In a similar manner to the sound experiment, to aid in the determining of the effect of the racket in the vibration measurements a modal analysis experiment was completed on the Dunlop 300G racket used in the experiment, the properties of which were presented in Chapter 1. The results of the modal analysis experiment are detailed in Table 5.6.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Longitudinal</td>
<td>142.5 Hz</td>
</tr>
<tr>
<td>2nd Longitudinal</td>
<td>345.9 Hz</td>
</tr>
<tr>
<td>1st Torsional</td>
<td>407.8 Hz</td>
</tr>
<tr>
<td>3rd Longitudinal</td>
<td>707.8 Hz</td>
</tr>
<tr>
<td>1st String</td>
<td>615.1 Hz</td>
</tr>
<tr>
<td>2nd String</td>
<td>987.6 Hz</td>
</tr>
</tbody>
</table>

Table 5.6: Table of racket (Dunlop 300G) natural frequencies for vibration experiment

A backhand punch volley was chosen as the shot for the test. The number of cables placed onto the player restricted their full range of motion, and hence a full-bodied backhand swing, or a service stroke, was not deemed appropriate. In order to simplify the movement of the player, a punch style volley was employed, with the players instructed to hit the same shot each time.

The players had accelerometers attached to them at the knuckle, wrist and elbow using the arrangement previously outlined. The cables were routed under a sweatband placed on the arm of the player and secured to the top of the arm, and to the back of the player’s shirt before being routed to the charge amplifiers and held securely out of the way.

The balls were delivered to the players via a modified BOLA ball-launching machine. The velocity of ball launch and the location of the machine were the same for all players. The BOLA machine is operated by two large rotating wheels that force the ball through a small aperture from which the ball is launched. No spin was imparted to the ball as both wheels were operated at the same velocity. There were small differences in impact velocity apparent due to the position that the player took at the net, as some preferred to stand closer to the net than others. In addition, due to the variation in size of the balls, small differences in ball velocity were apparent, though this was not quantified.
It has been found by Bowyer & Cross (2003) and Strode et al. (1999) that hearing has an effect on the players' perceptions. In order to further investigate this effect, ear defenders were used which incorporated loud speakers in the casing. These were attached to a small mp3 player, which was playing continuous pink noise at a level such that the sound of impact was totally excluded from the player.

The players were allowed multiple practise shots to get used to the delivery of the ball as well as the equipment that was attached to them, and the test only commenced once the players were happy and fully briefed as to the nature of the test.

The balls were fired in pairs in an order randomised through adoption of a Latin Square as in Table 5.5. The balls were launched sequentially with each ball being delivered in sequence A, B. This process was repeated three times, thus making six shots before each comparison. Once the six shots had been played the players were asked to answer each of the perception questions. This process was repeated for all other ball combinations as outlined in Table 5.5. During the test the players were asked to identify any mishits, so that this data could be removed from the objective analysis. In addition, in answering the perception questions, the players were asked only to consider the 'good' shots. Once all comparisons had been completed, the test was repeated with the ear defenders on. Hence, in total, twelve sets of comparisons were made, six with sound, and six with sound excluded.
CHAPTER 6

Sound and Vibration Subjective Data Analysis

This chapter outlines the analysis and results of the subjective data obtained during the sound and vibration tests. The subjective data, collected in the form of paired comparisons, was required to be transformed into scaled data so that it could be correlated with the objective data collected. The analysis procedure for the subjective data can be found in Figure 6.1.

6.1. Sound subjective data analysis

Each player's responses were entered into a score matrix to indicate each paired comparison result. An example score matrix is shown in Table 6.1 where a score of 1, 0 or 0.5 is assigned for answers of 'more pleasant', 'less pleasant', or 'no noticeable difference' respectively.

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Precision</th>
<th>Slazenger</th>
<th>Tretorn</th>
<th>Score (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>/</td>
<td>0.5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Precision</td>
<td>0.5</td>
<td>/</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Slazenger</td>
<td>1</td>
<td>1</td>
<td>/</td>
<td>1</td>
</tr>
<tr>
<td>Tretorn</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 6.1 - Typical player score matrix

A table was created for each player for each question, and the scores for each ball summed in order for each ball to achieve an overall score. These tables were then combined in order to find the total score for each of the balls ($a_i$).
The summed data for all players can be directly interpreted as a ranking. Table 6.2 shows the sum of scores for each question in the sound experiment. This is a simple method of analysing the data but it is not suitable for correlating with the objective data. This is because the scores say nothing about how one ball was judged against another. It is simply a method of displaying how one ball compares against the rest of the ball population (Otto et al., 2001). It is desirable to interpret the results in terms of scaled data, where each score is represented on a linear scale, so that it can be correlated with the objective measures at a later point in the analysis. In order to achieve this, a model is required to be fitted to the data.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>30</td>
<td>25.5</td>
<td>21.5</td>
<td>25.5</td>
<td>28</td>
<td>22.5</td>
<td>18</td>
<td>18.5</td>
</tr>
<tr>
<td>Precision</td>
<td>11</td>
<td>28.5</td>
<td>15</td>
<td>27</td>
<td>20.5</td>
<td>14</td>
<td>38</td>
<td>23.5</td>
</tr>
<tr>
<td>Slazenger</td>
<td>28.5</td>
<td>25.5</td>
<td>22</td>
<td>28.5</td>
<td>27.5</td>
<td>25.5</td>
<td>23</td>
<td>18.5</td>
</tr>
<tr>
<td>Tretorn</td>
<td>20.5</td>
<td>12.5</td>
<td>31.5</td>
<td>9</td>
<td>14</td>
<td>28</td>
<td>11</td>
<td>29.5</td>
</tr>
</tbody>
</table>

Table 6.2: All player score matrix for sound

### 6.1.1. Fitting a linear paired comparison model

A linear paired comparison model assumes that for each object in a paired comparison study, there exists a value called the merit value, \( V \), which underlies all the paired comparison judgements. These merit values lie along a linear scale and the relative position of each value is indicative of how the objects will be judged in the paired comparison. Therefore objects that have merit values that are close together should have ‘pair probabilities’ close to 0.5 while objects that are vastly different from one another should have ‘pair probabilities’ approaching 1 (Otto et al., 2001).

As the ‘merit’ of an object will vary from judge to judge, the value is not a constant, but a variable, \( y \) with a mean value of \( V \). The probability \( (\Pi_y) \) that object \( i \) is preferred to object \( j \) is given by Eq. 6.1.

\[
\Pi_y = \Pr(y_i > y_j) = \Pr(y_i - y_j > 0)
\]

Eq. 6.1
The normalised variables $z_i$ can be defined as $z_i = y_i - V_i$, and if it is assumed that all values of $z$ are independent and identically distributed, then the bivariate distributions $(z_i, z_j)$ are symmetrically distributed around zero. It can then be deduced (Otto, 1997) that:

$$\Pi_y = \Pr(z_i - z_j > (V_i - V_j)) = \Pr(z_i - z_j < (V_i - V_j))$$  \hspace{1cm} \text{Eq. 6.2}

If $H$ is defined as the cumulative distribution function (CDF) of $z_i - z_j$ then Eq. 6.2 may be rewritten as:

$$\Pi_y = H(V_i - V_j)$$  \hspace{1cm} \text{Eq. 6.3}

The preference probabilities can be estimated from the raw paired comparison data where:

$$\Pi_y \approx p_{ij} = \frac{\text{Number of comparisons where } i \text{ is preferred to } j}{\text{Total number of } ij \text{ comparisons}}$$  \hspace{1cm} \text{Eq. 6.4}

Hence the merit values can be estimated as:

$$V_i - V_j = H^{-1}(p_y)$$  \hspace{1cm} \text{Eq. 6.5}

This equation describes the general linear model for paired comparisons, with specific models distinguished by the distribution (H function) of $y_i$. The two popular models in use are the Thurstone Mosteller model, which uses normal variates (Thurstone, 1927), and the Bradley Terry model (Bradley, 1953), which uses doubly exponential variates. Otto & Wakefield (1993) reported that in over twenty-five acoustic perception studies the Bradley Terry model was superior to the Thurstone Mosteller model in fitting a model to the acoustic data. Therefore the Bradley Terry model was adopted for use in this research. The CDF for this model is given by Eq. 6.6.
Eq. 6.6 may be rewritten in terms of \( V_i \) which provides a means of calculating the merit values via the Bradley Terry model (Otto, 1997) as displayed in Eq. 6.7.

\[
p_y = H(V_i - V_j) = H(d_y) = \frac{1 + \tanh\left(\frac{d_y}{2}\right)}{2}
\]

Eq. 6.6

Where \( d_y = (V_i - V_j) \).

Eq. 6.7 permits the calculation of merit values for each object, \( i \), based on the ‘pair probabilities’. The process of calculating the merit values for all objects is displayed by the following simple example, for four objects, A, B, C and D and 12 judges. Table 6.3 presents the preference score matrix.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>4</td>
<td>-</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>D</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>-</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 6.3: Example preference score matrix

Each of the ball pair probabilities, \( p_y \) and \( p_{ji} \), are calculated for each object, \( i \), via means of Eq. 6.4, with the results presented in Table 6.4.

<table>
<thead>
<tr>
<th>( P_{AB} )</th>
<th>( P_{AC} )</th>
<th>( P_{AD} )</th>
<th>( P_{BC} )</th>
<th>( P_{BD} )</th>
<th>( P_{CD} )</th>
<th>( P_{CA} )</th>
<th>( P_{DA} )</th>
<th>( P_{CB} )</th>
<th>( P_{DB} )</th>
<th>( P_{DC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>0.50</td>
<td>0.42</td>
<td>0.67</td>
<td>0.67</td>
<td>0.42</td>
<td>0.83</td>
<td>0.50</td>
<td>0.58</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 6.4: Pair probabilities

There is a problem if either \( p_y = 1 \) or 0, due to taking logarithms of the result. In these scenarios the merit values are estimated as \( 1 - 1/4t \) and \( 1/4t \), which for when \( t = 4 \) is
equal to 0.9 and 0.1 respectively. The merit values may be calculated via Eq. 6.7 where for object A:

\[
V_A = \frac{\ln\left( \frac{P_{AB}}{P_{BA}} \right) + \ln\left( \frac{P_{AC}}{P_{CA}} \right) + \ln\left( \frac{P_{AD}}{P_{DA}} \right)}{4}
\]

Eq. 6.8

Similarly, merit values may be obtained for all other objects, as presented in Table 6.5.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_A)</td>
<td>-0.49</td>
</tr>
<tr>
<td>(V_B)</td>
<td>0.75</td>
</tr>
<tr>
<td>(V_C)</td>
<td>-0.26</td>
</tr>
<tr>
<td>(V_D)</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

Table 6.5: Merit values

The fit of the model may be analysed by determining the Pearson correlation coefficient \((r)\) of the model against the raw data, by recompiling the pair probabilities, using the merit values, according to Eq. 6.6. The Bradley Terry model outlined above was applied to each of the score matrices, for each question used in the sound experiment, with the results presented in Table 6.6.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>0.52</td>
<td>0.18</td>
<td>-0.05</td>
<td>0.18</td>
<td>0.30</td>
<td>0.00</td>
<td>-0.29</td>
<td>-0.22</td>
</tr>
<tr>
<td>Precision</td>
<td>-0.77</td>
<td>0.22</td>
<td>-0.42</td>
<td>0.32</td>
<td>-0.11</td>
<td>-0.50</td>
<td>1.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.36</td>
<td>0.19</td>
<td>-0.05</td>
<td>0.36</td>
<td>0.29</td>
<td>0.20</td>
<td>0.01</td>
<td>-0.22</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-0.11</td>
<td>-0.59</td>
<td>0.52</td>
<td>-0.85</td>
<td>-0.49</td>
<td>0.30</td>
<td>-0.73</td>
<td>0.39</td>
</tr>
<tr>
<td>(r)</td>
<td>0.95</td>
<td>0.91</td>
<td>0.92</td>
<td>0.97</td>
<td>0.94</td>
<td>0.91</td>
<td>0.98</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 6.6 – Bradley Terry sound merit values and model fit for all players

Values in the model range from +1.02 to -0.85. From analysis of the correlation coefficients \((r)\), it is apparent that the model accurately predicts the data for all questions, with a minimum Pearson correlation coefficient of 0.91, which is deemed as an acceptable fit by Otto et al. (2001).
be directly interpreted as scaled values and will be used in subsequent correlations. Figure 6.2a-h displays the merit values on a linear scale for all questions used in the analysis.

6.1.2. Statistical significance of results

From analysis of the paired comparison results it is possible to determine whether there are any statistically significant differences between the balls. The first test to complete is an overall test of equality, which is analogous to the F-test for analysing means in an analysis of variance (Starks & David, 1961).

The null hypothesis, \( H_0 : \Pi_i = 0.5 \), for all \( i \), with the alternative hypothesis, \( H_I: \) that not all the \( \Pi_i \) are equal.

A significance level of 0.05 (5%) was chosen for the analysis. To perform the test the value of \( D_n \) is calculated through the use of Eq. 6.9 (Starks & David, 1961).

\[
D_n = \frac{4 \left( \sum_{i=1}^{t} a_i^2 - \frac{1}{4} t n^2 (t-1)^2 \right)}{nt}
\]

Eq. 6.9

Where, as in previous analysis, \( t \) is the number of objects used, \( n \) the numbers of judges and \( a_i \) is the overall score for each ball. The value of \( D_n \) is compared with the upper \( \alpha \) significance point of the chi-square's distribution with \( t-1 \) degrees of freedom (Starks & David, 1961; David, 1988). For four objects, from the chi-square's tables, the upper significance point is 7.81. Hence, if the calculated value of \( D_n \) is above this value then the score may be deemed significant.

If a statistical difference between means is found, then it is desirable to know which balls are different from which. This process is analogous to carrying out paired t-tests (David, 1988). If no significant difference is found in the previous stage then no further analysis is required. Otherwise the critical value \( m_c \) is found through the use of Eq. 6.10a-b (Starks & David, 1961). Significantly different balls will have pairs of scores differing by \( m_c \) or greater.
\[ m_c = 1.96\sigma + 0.5 \quad \text{Eq. 6.10a} \]

where \( \sigma = \left( \frac{1}{2} n t \right)^{\frac{1}{2}} \quad \text{Eq. 6.10b} \)

Table 6.7 outlines the results from an overall test of equality for the sound data. Significant values of \( D_n \) at 5% are highlighted where calculated values of \( D_n \) exceed the upper significance point of 7.81.

<table>
<thead>
<tr>
<th>Question</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_n )</td>
<td>15.23</td>
<td>8.93</td>
<td>9.23</td>
<td>16.50</td>
<td>8.77</td>
<td>7.43</td>
<td>26.20</td>
<td>5.47</td>
</tr>
<tr>
<td>Significant at 5%</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 6.7 – Overall test of equality for all players’ results

It is apparent from Table 6.7 that only two of the questions do not show significant subjective differences between balls, those being the duration of the sound and the controllability of the ball. Those questions displaying the greatest differences between balls are the perceived speed of the ball, pitch and pleasantness.

Through the use of Eq. 6.10a-b a value of \( m_c \) is calculated as 12. Hence, any balls whose scores \( (a_i) \) differ by more than this amount may be considered statistically different from each other. The scores for each ball, for each question, are provided in Table 6.2. Only questions where significant differences between means were found in the previous stage were included in the analysis. Figure 6.3 shows the output of the multiple t-tests being performed on the data from Table 6.2, with statistically significant results highlighted where appropriate. No significant differences are found between the Slazenger and Absorber for any sound question.
6.1.3. Sound experiment player reliability

Through the use of the consistency test outlined in section 5.3 it is possible to determine the reliability of each player for each question answered. Through this analysis it is possible to determine which players may be deemed unreliable and hence remove their data, before reanalysing the remaining data.

By taking each individual player's score matrix, it is possible to determine a consistency score for each question, through the evaluation of triads as outlined in Chapter 5. By summing the player's score over all questions, it is possible to determine the probability of the player obtaining that score by chance. A limit can then be applied, for example 5% and any players scoring higher than this may be deemed unreliable.

Table 6.8 displays the consistency scores for all players for each question used in the sound analysis. In Chapter 5, a scoring system was introduced where an increased score implies an increased inconsistency of response.

<table>
<thead>
<tr>
<th>Question</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Less Pleasant</td>
<td>Hard</td>
<td>Heavy</td>
<td>Higher Pitch</td>
<td>Loud</td>
<td>Longer duration</td>
<td>Quicker</td>
<td>More control</td>
</tr>
<tr>
<td></td>
<td>More pleasant</td>
<td>Soft</td>
<td>Light</td>
<td>Lower Pitch</td>
<td>Quiet</td>
<td>Shorter duration</td>
<td>Slower</td>
<td>Less control</td>
</tr>
<tr>
<td>Consistency</td>
<td>4.5</td>
<td>8</td>
<td>9</td>
<td>7.50</td>
<td>8.25</td>
<td>12.25</td>
<td>5</td>
<td>6.50</td>
</tr>
<tr>
<td>Avg Consistency</td>
<td>0.30</td>
<td>0.53</td>
<td>0.60</td>
<td>0.50</td>
<td>0.55</td>
<td>0.62</td>
<td>0.33</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 6.8 – Consistency scores per question for all players

From Table 6.8 it is apparent that there is a large range in the results of the consistency scores, with the average consistency score of perceived duration of ball sound being almost three times that of the pleasantness of the ball. This shows that players were able to reliably determine ball pleasantness, but had difficulty in determining the duration of ball sound.

A consistency score was then calculated for each player used in the analysis, with the results presented in Table 6.9, together with a probability (p) of the player achieving that score by chance attained from Figure 5.1.
The consistency scores in Table 6.9 range from 0.5 to 8. It is apparent from the analysis of the players’ probabilities of achieving their consistency score by chance that three players, namely players 8, 10 and 15, fall outside of the ‘pass’ region set at 5%. These players are deemed to have ‘failed’ the consistency test and their data will be removed from the subsequent analysis.

Table 6.10 displays the results of the Bradley Terry analysis as completed for Table 6.6 but with the unreliable players removed. The fit has generally been improved, as shown by the increases in the Pearson correlation coefficient. This is due to the fact that the Bradley Terry model does not fit optimally when there are inconsistencies in the data (Otto et al., 2001). In addition the range of merit values has been increased, indicative of exaggerated differences between balls.

Table 6.11 displays the results of a further equality of means test for the sound data, with the data for unreliable players removed.
Comparing Table 6.11 and Table 6.7, it is apparent that through the removal of unreliable players, the significance of the results is increased, as displayed by an increase in the value of $D_n$. Indeed, all results are now significant at the 5% level. The highest value of significance remains the question regarding the perceived speed of the ball off the racket face, with perceived loudness and control displaying the least significance.

### 6.1.4. Sound perception correlation

Through the use of the Pearson correlation coefficient it is possible to correlate each of the perception questions with each other. This is achieved through the correlation of the merit values for each question, with the results indicating any relationships between the questions.

As has been shown, the model fit is improved through the removal of players that have been deemed unreliable, so only the reliable players' responses will be analysed. Table 6.12 outlines the Pearson correlation coefficient ($r$) for all questions.

<table>
<thead>
<tr>
<th>Q</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>/</td>
<td>0.27</td>
<td>0.32</td>
<td>0.32</td>
<td>0.83</td>
<td>0.56</td>
<td>-0.30</td>
<td>-0.56</td>
</tr>
<tr>
<td>2</td>
<td>/</td>
<td>-0.79</td>
<td>1.00</td>
<td>0.76</td>
<td>-0.81</td>
<td>0.83</td>
<td>-0.95</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>/</td>
<td>-0.77</td>
<td>-0.25</td>
<td>0.96</td>
<td>-0.91</td>
<td>0.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>/</td>
<td>0.79</td>
<td>-0.58</td>
<td>0.80</td>
<td>-0.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>/</td>
<td>0.02</td>
<td>0.27</td>
<td>-0.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>/</td>
<td>-0.89</td>
<td>0.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>/</td>
<td>-0.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>/</td>
<td>/</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.12 – Pearson correlation coefficient ($r$) for sound questions for reliable players
As there are only four data points for each correlation, a Pearson correlation coefficient of \( \pm 0.95 \) represents a significance level of 5%, and a value of \( \pm 0.90 \) represents a significance level of 10%.

Significant values of \( r \) are found at the 5% level between the hardness of feel and the pitch of the ball sound and level of control, with a harder ball perceived to be higher in pitch and less controllable. Whilst not significant at the 10% level, the results suggest that a perceived harder ball also correlates strongly with the remaining questions, indicating a harder ball is perceived to be louder, faster off the racket and possesses a shorter duration sound.

A significant correlation is found between the perceived weight of the ball, and both the perceived duration of ball sound and the speed of ball off the racket face, with a heavy ball producing a perceived longer duration sound, and is perceived to be slower off the racket face.

Significant correlations are found between the perceived level of control and the pitch and loudness of ball sound, with a perceived loss of control for loud and high pitched sounds. Ball pleasantness does not correlate at the 10% significance level or greater with any of the questions.

6.2. Vibration subjective data analysis

Similarly to the sound subjective data analysis, each vibration question was initially combined into a score matrix, with the results presented in Table 6.13.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>56</td>
<td>43.5</td>
<td>48</td>
<td>31.5</td>
<td>40</td>
</tr>
<tr>
<td>Precision</td>
<td>34</td>
<td>52</td>
<td>37.5</td>
<td>48</td>
<td>59.5</td>
</tr>
<tr>
<td>Slazenger</td>
<td>43.5</td>
<td>46</td>
<td>38</td>
<td>42</td>
<td>45.5</td>
</tr>
<tr>
<td>Tretorn</td>
<td>34.5</td>
<td>26.5</td>
<td>46.5</td>
<td>46.5</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 6.13: All player score matrix for vibration
As with the sound data, whilst Table 6.13 can be directly interpreted as a ranking, it is desirable to convert the values to scaled data through the application of the Bradley Terry linear paired comparison model. Tables 6.14a-c outline the results of this analysis, split into three sections, where the comparisons were made ‘with sound’, ‘without sound’ and the results combined, as outlined in Chapter 5.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>+ More pleasant</td>
<td>- Less Pleasant</td>
<td>+ Soft</td>
<td>- Hard</td>
<td>- Heavy</td>
</tr>
<tr>
<td>Precision</td>
<td>-0.38</td>
<td>0.32</td>
<td>-0.26</td>
<td>0.23</td>
<td>0.56</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.12</td>
<td>0.04</td>
<td>-0.18</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-0.28</td>
<td>-0.49</td>
<td>0.20</td>
<td>0.21</td>
<td>-0.66</td>
</tr>
<tr>
<td>$r$</td>
<td>0.98</td>
<td>0.93</td>
<td>0.91</td>
<td>0.92</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 6.14a – Bradley Terry vibration merit values and model fit for all players ‘with sound’

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>+ More pleasant</td>
<td>- Less Pleasant</td>
<td>+ Soft</td>
<td>- Hard</td>
<td>- Heavy</td>
</tr>
<tr>
<td>Precision</td>
<td>-0.12</td>
<td>0.28</td>
<td>0.00</td>
<td>0.11</td>
<td>0.53</td>
</tr>
<tr>
<td>Slazenger</td>
<td>-0.04</td>
<td>0.21</td>
<td>-0.06</td>
<td>-0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-0.17</td>
<td>-0.46</td>
<td>0.06</td>
<td>0.06</td>
<td>-0.53</td>
</tr>
<tr>
<td>$r$</td>
<td>0.83</td>
<td>0.97</td>
<td>0.50</td>
<td>0.93</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 6.14b – Bradley Terry vibration merit values and model fit for all players ‘without sound’

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>+ More pleasant</td>
<td>- Less Pleasant</td>
<td>+ Soft</td>
<td>- Hard</td>
<td>- Heavy</td>
</tr>
<tr>
<td>Precision</td>
<td>-0.24</td>
<td>0.04</td>
<td>0.12</td>
<td>-0.31</td>
<td>-0.06</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.04</td>
<td>0.30</td>
<td>-0.13</td>
<td>0.17</td>
<td>0.54</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-0.22</td>
<td>-0.47</td>
<td>0.13</td>
<td>0.13</td>
<td>-0.59</td>
</tr>
<tr>
<td>$r$</td>
<td>0.99</td>
<td>0.98</td>
<td>0.83</td>
<td>0.93</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 6.14c – Bradley Terry vibration merit values and model fit for all players combined results
For the vibration data, the merit values range from $+0.56$ to $-0.66$, indicating that the differences between balls in the vibration experiment were less marked than in the sound experiment. There are two questions, pleasantness and heaviness, where the model does not fit well with the data, both being in the 'without sound' data, indicated by a low value of Pearson correlation coefficient. It is apparent from the range of merit values for the question on heaviness that there is very little difference between the balls, with values ranging from $-0.06$ to $+0.06$. Additionally the model fit may be poor due to inconsistencies in the responses, as well as a lack of agreement between players. These will be discussed in a later section.

Figures 6.4a-e display the merit values on a linear scale for the 'with sound', 'without sound' and combined results. It is clear from the figures that the players' ability to distinguish between balls diminishes when sound is excluded from the experiment.

### 6.2.1. Statistical significance of vibration results

Tables 6.15a-c outline the results from an overall test of equality for the vibration data for the two testing environments, 'with sound' and 'without sound', as well as the combined results. Once again a value of $D_n$ of greater than 7.81 is deemed significant at the 5% level.

#### Table 6.15a – Overall test of equality 'with sound' results

<table>
<thead>
<tr>
<th></th>
<th>1 - Less Pleasant + More pleasant</th>
<th>2 - Hard + Soft</th>
<th>3 - Heavy + Light</th>
<th>4 - Less Vibration + More Vibration</th>
<th>5 - Faster + Slower</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_n$</td>
<td>9.46</td>
<td>7.04</td>
<td>4.11</td>
<td>7.96</td>
<td>13.96</td>
</tr>
<tr>
<td>Significant</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

#### Table 6.15b – Overall test of equality 'without sound' results

<table>
<thead>
<tr>
<th></th>
<th>1 - Less Pleasant + More pleasant</th>
<th>2 - Hard + Soft</th>
<th>3 - Heavy + Light</th>
<th>4 - Less Vibration + More Vibration</th>
<th>5 - Faster + Slower</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_n$</td>
<td>3.11</td>
<td>6.36</td>
<td>0.14</td>
<td>0.68</td>
<td>10.64</td>
</tr>
<tr>
<td>Significant</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>
From analysis of Tables 6.15a-b it is apparent that the players are less able to distinguish the differences between the balls when sound is excluded from the impact, with the value of $D_a$ being decreased in all cases. For the results in the test configuration ‘with sound’, significant differences are found between balls for perceptions of pleasantness, vibration and speed off the racket, whereas for the results ‘without sound’ only differences in the perceived speed of the ball are significant. For the combined results, significant results are obtained for questions on pleasantness, hardness and perceived speed.

It is possible to deduce from the analysis that the players had trouble distinguishing the weight of the ball at impact, with no significant differences being found in either test scenario. The perception of vibration levels displays the greatest differences between the two tests, as the value of $D_a$ decreased significantly between testing scenarios.

6.2.2. Vibration experiment player reliability

As for the sound data, consistency scores were calculated for each vibration question, using the scoring system outlined in Chapter 5. The results for all players are presented in Table 6.16a for the test scenario ‘with sound’ and Table 6.16b for the test scenario ‘without sound’.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Less Pleasant</td>
<td>-Hard</td>
<td>- Heavy</td>
<td>- Less Vibration</td>
<td>- Faster</td>
</tr>
<tr>
<td>+ More pleasant</td>
<td>+ Soft</td>
<td>+ Light</td>
<td>+ More Vibration</td>
<td>+ Slower</td>
</tr>
<tr>
<td>$D_a$</td>
<td>11.38</td>
<td>12.80</td>
<td>2.59</td>
<td>5.95</td>
</tr>
</tbody>
</table>

| Significant | Y | Y | N | N | Y |

Table 6.15c – Overall test of equality combined results

Table 6.16a – Consistency scores per question for all players ‘with sound’

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Less Pleasant</td>
<td>-Hard</td>
<td>- Heavy</td>
<td>- Less Vibration</td>
<td>- Faster</td>
</tr>
<tr>
<td>+ More pleasant</td>
<td>+ Soft</td>
<td>+ Light</td>
<td>+ More Vibration</td>
<td>+ Slower</td>
</tr>
<tr>
<td>Consistency</td>
<td>7.50</td>
<td>8.75</td>
<td>10.00</td>
<td>12.25</td>
</tr>
<tr>
<td>Avg Consistency</td>
<td>0.54</td>
<td>0.63</td>
<td>0.71</td>
<td>0.88</td>
</tr>
</tbody>
</table>
There are clear differences between the consistency scores between test structures. For the questions of pleasantness, hardness, and perceived speed the score is increased, indicating a decrease in consistency of the responses. The consistency score of the perceived weight of impact remains constant, whereas the consistency of responses of the perception of vibration is increased. Once again, these differences between test structures indicate that the ball sound does have a psychological impact on the players’ perceptions. This may be a negative effect on the perception of pleasantness, hardness and perceived speed, but have a positive influence on the perception of vibration.

Table 6.16b presents the individual consistency scores for all players used in the analysis, in both test scenarios, together with the probability \( (p) \) of the player achieving that score by chance, as obtained from Figure 5.1.

As with the sound experiment, if a pass region is set at 5%, it is apparent that only three players passed both tests, namely players 2, 4 and 8. Comparing the test structures, six players passed the ‘with sound’ test (Players 1, 2, 4, 5, 8, 10) and five the ‘without sound’ test (Players 2, 4, 6, 8, 14). Players 6 & 14, failed the ‘with sound’ test.

### Table 6.16b - Consistency scores per question for all players ‘without sound’

<table>
<thead>
<tr>
<th>Question</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Less P</td>
<td>More P</td>
<td>Less H</td>
<td>More H</td>
<td>Faster</td>
</tr>
<tr>
<td></td>
<td>pleasant</td>
<td>pleasant</td>
<td>Hard</td>
<td>Soft</td>
<td>Slower</td>
</tr>
<tr>
<td>Consistency</td>
<td>10.75</td>
<td>12.00</td>
<td>10.00</td>
<td>9.75</td>
<td>10.25</td>
</tr>
<tr>
<td>Avg Consistency</td>
<td>0.77</td>
<td>0.86</td>
<td>0.71</td>
<td>0.70</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Table 6.17 - Consistency scores per player for vibration test protocols ‘with sound’ and ‘without sound’

<table>
<thead>
<tr>
<th>Player</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5</td>
<td>1</td>
<td>4.75</td>
<td>1.25</td>
<td>2.5</td>
<td>3.75</td>
<td>3</td>
<td>0</td>
<td>3.5</td>
<td>2.5</td>
<td>7</td>
<td>3</td>
<td>4.75</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>0.00</td>
<td>0.46</td>
<td>0.00</td>
<td>0.03</td>
<td>0.19</td>
<td>0.07</td>
<td>0.00</td>
<td>0.15</td>
<td>0.03</td>
<td>0.95</td>
<td>0.07</td>
<td>0.46</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>5.75</td>
<td>2.5</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>5.25</td>
<td>0</td>
<td>8.75</td>
<td>3.25</td>
<td>4.75</td>
<td>5.75</td>
<td>5</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.03</td>
<td>0.54</td>
<td>0.00</td>
<td>0.54</td>
<td>0.00</td>
<td>0.61</td>
<td>0.00</td>
<td>0.93</td>
<td>0.11</td>
<td>0.46</td>
<td>0.75</td>
<td>0.54</td>
<td>0.05</td>
</tr>
</tbody>
</table>
sound' vibration test structure and passed the 'without sound' part of the test. Inconsistency scores tended to increase when sound was removed, however, there are a number of reasons why such an increase in reliability between test structures could occur on an individual basis. For example, the 'without sound' test always followed the 'with sound' test and hence the player may have become more comfortable with the test procedure and equipment used. The use of ear defenders may also have blocked out any distracting noise from the tennis centre thus allowing the player full concentration.

Combining scores for both test structures it is found that five players (Players 2, 4, 6, 8 & 10) have a score with cumulative probability of less than 5% for the ten questions used. Table 6.18a-c presents revised merit values for only these players, for both test scenarios and a combined result.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>0.69</td>
<td>0.36</td>
<td>0.53</td>
<td>-0.83</td>
<td>0.08</td>
</tr>
<tr>
<td>Precision</td>
<td>0.11</td>
<td>0.52</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.53</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.36</td>
<td>0.28</td>
<td>-0.10</td>
<td>0.00</td>
<td>0.44</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-1.16</td>
<td>-1.16</td>
<td>-0.42</td>
<td>0.83</td>
<td>-1.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>0.55</td>
<td>-0.01</td>
<td>0.15</td>
<td>0.01</td>
<td>0.17</td>
</tr>
<tr>
<td>Precision</td>
<td>0.17</td>
<td>0.69</td>
<td>0.25</td>
<td>-0.42</td>
<td>0.80</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.00</td>
<td>0.12</td>
<td>-0.16</td>
<td>-0.12</td>
<td>-0.08</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-0.72</td>
<td>-0.80</td>
<td>-0.25</td>
<td>0.53</td>
<td>-0.89</td>
</tr>
</tbody>
</table>

Table 6.18a – Bradley Terry merit values and model fit for reliable players for vibration experiment 'with sound'

Table 6.18b – Bradley Terry merit values and model fit for reliable players for vibration experiment 'without sound'
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>-0.60</td>
<td>0.17</td>
<td>0.30</td>
<td>-0.38</td>
<td>0.13</td>
</tr>
<tr>
<td>Precision</td>
<td>0.14</td>
<td>0.75</td>
<td>0.12</td>
<td>-0.22</td>
<td>0.64</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.27</td>
<td>0.28</td>
<td>-0.10</td>
<td>-0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>Tretorn</td>
<td>-1.01</td>
<td>-1.20</td>
<td>-0.33</td>
<td>0.67</td>
<td>-1.05</td>
</tr>
<tr>
<td>r</td>
<td>0.97</td>
<td>0.95</td>
<td>0.80</td>
<td>0.94</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Table 6.18c – Bradley Terry merit values and model fit for reliable players for vibration experiment combined results

Table 6.19 displays the results of a further equality of means test for the combined vibration data using only those players that have a consistency score with cumulative probability of less than 5% for the ten questions used.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_n</td>
<td>14.85</td>
<td>16.05</td>
<td>3.15</td>
<td>8.30</td>
<td>14.85</td>
</tr>
</tbody>
</table>

Table 6.19 – Analysis of means for reliable players for combined results

Comparing Table 6.19 and Table 6.15c, it is again apparent that through the removal of players deemed unreliable, the significance of the results are increased, as displayed by an increase in the value of $D_n$. Only the perceived speed of the ball decreases in significance, though this is primarily due to the lower number of comparisons made by the five reliable players. The perceived level of vibration is now significant, suggesting that subjective assessment of vibration level is a non-trivial task only possible by the most skilled players.

Whilst the significance level for the perceived weight of the ball responses is slightly improved, it remains insignificant. As only players that have been deemed reliable are included in the analysis, this suggests that players are either incapable of discriminating between ball weight, or that there is a lack of agreement between players.
6.2.3. Repeatability analysis for vibration experiment

Due to the way that the vibration test was performed, it is possible to judge a player’s repeatability over the two testing scenarios ‘with sound’ and ‘without sound’. For the situation where only two options are presented to the judges Otto & Wakefield (1993) define the repeatability as:

\[
\text{Repeatability} = \frac{\text{Number of pairs with same selection for both trials}}{\text{Total number of pairs}}
\]

Eq. 6.11

For the situation where there is an option of ‘no noticeable difference’ the repeatability may be defined as:

\[
\text{Repeatability} = \frac{\sum_{i=1}^{n} (\text{score for first comparison} - \text{score for second comparison})}{\text{Total number of comparisons}}
\]

Eq. 6.12

Clearly, from Eq. 6.12, if the player’s responses are the same for both test structures then the repeatability score will be zero. If a player reverses their decision between test structures then a score of one is obtained. It is anticipated that the repeatability score may indicate differences in perception caused through the variation in testing scenario i.e. through the removal of sound. Table 6.20 displays the repeatability scores for all players, for each of the questions used in the analysis.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Less Pleasant</td>
<td>More pleasant</td>
<td>Hard</td>
<td>Heavy</td>
<td>Less Vibration</td>
</tr>
<tr>
<td>Avg Repeatability</td>
<td>0.33</td>
<td>0.31</td>
<td>0.31</td>
<td>0.35</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 6.20 – Average repeatability scores for all players

From Table 6.20 it is apparent that repeatability scores are similar for all questions, with the vibration question being the least repeatable. This would indicate that the perception of vibration is the most affected through the removal of sound.
6.2.4. Vibration perception correlation

As with the subjective sound data, the Pearson correlation coefficient may be used to highlight any relationships between the vibration questions. Table 6.21 displays this analysis for those players deemed reliable, using the combined scores of the ‘with sound’ and ‘without sound’ test structures.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>/</td>
<td>0.85</td>
<td>0.88</td>
<td>-0.98</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>/</td>
<td>0.74</td>
<td>/</td>
<td>-0.90</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>/</td>
<td>/</td>
<td>-0.93</td>
<td>/</td>
<td>-0.99</td>
</tr>
<tr>
<td>4</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 6.21 – Pearson correlation coefficient for combined vibration questions for reliable players

As there are only four data points for each correlation a Pearson correlation coefficient of $\pm 0.95$ represents a significance level of 5%, and a value of $\pm 0.90$ represents a significance level of 10%.

Strong trends are apparent for all combinations of questions, with the minimum correlation coefficient obtained of +0.72. Significant values at the 5% level are found between the perceived level of vibration and the pleasantness of the ball, with a pleasant ball perceived as causing low levels of vibration. In addition the perceived level of vibration is significantly correlated at the 10% level with the perceived hardness and weight of the ball, with a softer and lighter ball also perceived as causing low levels of vibration.

A further significant correlation at the 5% level is found between the perceived speed of the ball off the racket and the hardness of the ball, with a softer ball perceived as leaving the racket face more slowly.

The correlation coefficients for all questions relating to pleasantness indicate that the players prefer a softer, lighter, low vibration and slower ball. It is of interest to compare these findings to that of the ‘ideal feel’ of a tennis ball outlined in Chapter 2.
In that study it was found that the 'ideal feel' would be from a harder, heavier, quicker ball which caused low levels of vibration.

6.3. Comparisons between test protocols

The two perception studies were completed with a similar standard of players, using the same balls, in similar conditions, and there was some repetition of questioning. There are a number of factors differing between the two tests, including the equipment used, the number of questions asked, and the number of shots completed before a comparison was made, all which may have had an effect on the players' perceptions of the balls.

During the sound experiment, the players were free to see and handle the balls whereas in the vibration experiment the players were unaware of the balls used, due to the test structure. In addition, the different shots used during the two experiments (serve and volley) may have an effect on the perception of the balls due to the relative ball speeds, with the service shot being a significantly higher impact speed.

The differences between the consistency scores in the two experiments are large. Three players failed the sound consistency test, whereas only three passed both vibration consistency tests successfully. This could be due to a variety of factors, including the difference between the test protocols, the fact that the vibration test was effectively blind, and that the pink noise played to the players could have been distracting. The average scores for each consistency test are outlined in Table 6.22.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Average Consistency Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>0.44</td>
</tr>
<tr>
<td>Vibration 'with sound'</td>
<td>0.64</td>
</tr>
<tr>
<td>Vibration 'without sound'</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 6.22 – Average consistency scores per test protocol
The following chapter outlines the analysis of the objective data collected in the sound and vibration experiments. Metrics for both sound and vibration were chosen that may correlate with human perceptions, with the resulting analysis presented in this chapter.

7.1. Sound objective analysis
The sound recorded at impact is a combination of ball, racket and background noise. In order to commence the analysis, and to highlight where differences may be found between balls, a simple experiment was undertaken to elicit the differences between balls in a quiet laboratory environment.

Each of the four balls used in the sound experiment were dropped onto a hard surface with the resulting impact recorded through the use of a Bruel and Kjaer Type 2238 sound level meter, positioned at a point close to the impact location. A location was chosen where background noise was kept to a minimum. As per the sound experiment outlined in Chapter 5, the data was collected by a computer based multi-channel, data acquisition system at a sampling rate of 51.2kHz. The capture was pre-triggered to ensure the start of impact was collected, and a low pass filter of 20kHz was applied. The data was A-weighted at sound capture.
Fifty impacts were collected for each ball used in the analysis. Figure 7.1a-b displays the averaged spectra, for each of the four balls used, over ranges of 0-10kHz and 0-3kHz respectively. There was found to be very little content above 10kHz.

In order to determine the reliability of the method, individual sound spectra were randomly chosen and matched to a corresponding ball with a very high level of accuracy, thus indicating that ball sound spectra can be differentiated in a quiet laboratory environment.

Below 500Hz the frequency spectrums are very similar. Whilst the peaks are near coincident, the amplitudes are varied across balls with the Precision yielding the highest amplitudes. The frequency range between approximately 500-900Hz contains little content for all balls used, with the exception of a peak at approximately 600Hz, again most significant for the Precision. Above 900Hz significant differences are found in both amplitude and frequency content. The Slazenger Wimbledon and Dunlop Absorber have similar content with peaks around 900Hz, 1100Hz and 1300Hz. The Dunlop Precision has a broader range of frequencies rising to a peak at around the 1500Hz mark. The Tretorn is particularly distinguishable with a dominant peak at approximately 1300Hz.

As a tennis racket is not as stiff as the hard surface from which the frequency spectrums were calculated, it is likely that the higher modes will not be excited in such a large proportion during the actual racket tests. However, as the frequencies in the region above 1kHz are more perceivable than those frequencies at the lower end of the spectrum, it is likely that such differences in higher frequency content may contribute largely to the perceived differences in impact sound. Differences in natural frequencies were highlighted in the modal analysis tests in Chapter 2, however, no results were obtained for frequencies greater than 1kHz, due to a lack of coherence in the measurements.

Whilst this simple experiment goes some way to explain the differences in ball sound, tennis players do not play in such an environment and hence it is of interest to see whether such differences can be perceived and recorded in actual tennis playing conditions.
7.1.1. Calculation of sound metrics

The first stage of the sound objective analysis was to remove data that had been corrupted either through player's mishits, through equipment failure or overload of the sound level meter or racket-mounted accelerometer. In total 910 'good' shots resulted from 1060 service shots recorded. Checks were made as to the consistency of the data, through graphical analysis of the data.

Initially, seven metrics were chosen that may correlate with the perception of the impact sound.

i. Peak level (dB(A)) – the largest recorded value for each measurement
ii. Peak-to-peak value (dB(A)) – the difference between the maximum and minimum value from each sound trace
iii. SPL (dB(A)) of the first 10 milliseconds – the SPL over the first 10 milliseconds of impact
iv. SPL (dB(A)) of the entire trace – the SPL over the entire 80 milliseconds of data.
v. Decay – the power of the exponential curve that best fits the data
vi. Duration (ms) – the time taken for the SPL to drop 25dB from the peak level
vii. Centroid of frequency spectrum (Hz) – The centroid of the frequency spectrum calculated through the use of one-third octave bands.

The first four metrics were designed to correlate with the perception of loudness. The SPL was calculated over both 10 and 80 ms of data. It became apparent that the majority of the sound of the impact was contained in the first 10ms of data, as is displayed for a sample sound capture in Figure 7.2. Therefore, through only analysing this region, it was expected that there would be less influence from noise. As the tests were conducted indoors, reflections off the floor, roof and walls are likely to be present in the 80ms of data. In addition there is a peak at approximately 12ms, identified as the player's front foot landing after the service action.

Two metrics were chosen to represent the duration of the ball sound. The decay metric fits an exponential curve of the type $y(t) = be^{-at}$ to the first 10ms of the sound
data. The resulting decay curve is displayed in Figure 7.3 for the sample data displayed in Figure 7.2. The absolute values of the data were used for the first 10ms of the trace. For each successive half millisecond of data, the maximum absolute measurement was determined and the decay envelope fitted to these points. The decay of the sound is quantified by the coefficient $c$. A second metric to represent the duration of the sound was calculated as the time for the average SPL, for each successive half-millisecond of data, to drop 25dB from its peak level. A value of 25dB was arbitrarily defined, as this was found to be the longest data length that could be consistently considered for all players, without the level of background noise becoming a factor.

A final metric was chosen to represent the frequency content of the sound which may relate to the pitch of the ball sound through the use of one-third octave bands (McAdams et al., 1999; Roberts, 2002). Eq. 7.1 calculates the centroid of the frequency spectrum, where $s_i$ is the SPL in each one-third octave band, with the centre frequencies of each one-third octave band used as values of $f_i$. Through the adoption of this equation a single value of frequency can be found that is representative of a complex frequency spectrum. The lowest third octave band used was 100Hz due to the frequency of resolution of the spectrum.

$$f_c = \frac{\sum_{i=1}^{N} s_i f_i}{\sum_{i=1}^{N} s_i}$$

Eq. 7.1.

Each metric was calculated for every player for all shots recorded. An average value for each player was determined to highlight differences between players. Figure 7.4 displays each player’s average peak-to-peak level for all balls used. It is clear that there are significant differences present between players, which may be attributed to a number of factors, including the level of background noise in the tennis centre, the impact speed and the location of impact and associated distance from the microphone. The data was then combined on a ball-by-ball basis for all players used in the analysis for each metric and Table 7.1 produced.
Peak | Peak-to-peak | RMS (10ms) | RMS (80 ms) |
--- | --- | --- | --- |
Absorber | 113.07 2.57 | 117.71 2.34 | 110.37 4.45 | 95.04 4.26 |
Precision | 113.27 2.93 | 118.24 2.75 | 110.89 5.18 | 95.19 4.68 |
Slazenger | 112.78 2.88 | 117.40 2.80 | 110.36 5.21 | 95.04 4.87 |
Tretorn | 113.51 3.05 | 118.42 2.99 | 111.73 5.22 | 96.32 4.99 |

Table 7.1 – Summary table for all metrics per ball

Whilst the Tretorn ball yields the highest values for all four loudness metrics, the maximal difference between balls is approximately 1.5dB(A). It has been shown (Chapter 4) that in an optimal environment, the minimal perceivable difference of loudness of pure tones is approximately 3dB. Therefore it is unlikely that players' perceptions of ball loudness are purely based on a direct perception of the SPL, and the relationship will be more complex.

The two methods of calculation of the ball sound duration yield consistent results, with the ordering of balls the same for both. The Precision is found to have the highest decay power, and also the shortest time period to fall 25dB from its peak at 6.95ms. The maximum difference between balls is 0.75ms or 10%. Finally, considering the centroid of the spectrum, it is apparent that the Precision yields the highest value of 1678Hz. The difference between it and the lowest value, the Slazenger, is 125Hz, which, according to the literature outlined in Chapter 4, may be perceivable.

It is apparent that the balls used can be divided into two groups, with the Tretorn and Precision yielding higher values of SPL, shorter durations and higher frequency content. Conversely, the Slazenger and Absorber produce a lower value of SPL, have a longer duration sound and contain lower frequency components.
In order to determine whether the differences measured were caused by random scatter or whether the results are statistically significant, a one-way ANOVA was completed. The results indicate the probability that all four balls have the same mean. The results of this analysis are presented in Table 7.2.

<table>
<thead>
<tr>
<th></th>
<th>Peak</th>
<th>Peak-to-peak</th>
<th>RMS (10ms)</th>
<th>RMS (80 ms)</th>
<th>Decay power</th>
<th>25dB drop</th>
<th>Centroid</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.21</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.10</td>
<td>0.08</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 7.2 — Result of one-way ANOVA

It is apparent from Table 7.2 that statistically significant results (at the 5% level) are found for peak-to-peak level, RMS (10ms & 80ms) and the centroid of the frequency spectrum. It is important to note that although significant differences have been found for peak-to-peak and other values, it does not indicate that players can perceive this difference. Due to the large quantity of data obtained, small differences may become statistically significant.

As displayed in Figure 7.4 the variability between players is fairly large, with means varying from approximately 6Pa to 13Pa. Hence a method of normalisation of the data was applied.

For each player the overall mean ($\mu$) and standard deviation ($\sigma$) for all shots were calculated. For every individual shot ($X$), the normalised value ($Z$) was calculated through the use of Eq. 7.2. This ensures that all players have a mean value of 0, and hence each player’s results can be better compared.

$$Z = \frac{X - \mu}{\sigma}$$

Eq. 7.2.

The data was then recombined for all balls and the results are presented in Table 7.3.
Table 7.3: Normalised results for all balls

Whilst the results obtained are similar in terms of ordering of balls to those obtained before normalisation, a study of the results of a one-way ANOVA, presented in Table 7.4, indicates that the significance levels have increased for all metrics used. Following the normalisation procedure, all metrics are found to be significant at the 5% level.

Table 7.4: Results of one-way ANOVA for normalised results

As discussed in Chapter 4, human hearing is a complex process, and the use of simple ‘raw’ metrics may not be appropriate for correlation with the subjective data. Therefore, the two commonly used psychometric metrics of Zwicker loudness (BS 4198, 1967) and sharpness (Aures, 1985) were calculated. Values of Zwicker loudness were obtained through the use of a computer script developed at Herrick Laboratories and Purdue University. The sharpness may then be calculated through the known values of Zwicker loudness and specific loudness according to Aures (1985). The resulting analysis is presented in Table 7.5 for each of the balls used in the analysis.
Table 7.5: Results of psychoacoustic calculations

Once again a one-way ANOVA was completed to determine the statistical significance of the differences between balls with the results presented in Table 7.6.

Table 7.6: Results of one-way ANOVA for psychoacoustic calculations

Once again, there is a clear benefit, as shown by the increased significance of results, in using the sound data over the first 10ms of impact as compared to 80ms. Finally as with previous metrics the data was normalised for each player, with the results presented in Table 7.7 and the resulting one-way ANOVA in Table 7.8.

Table 7.7: Results of normalised psychoacoustic calculations

It is evident from both sets of analysis that there is little difference between the loudness metrics measured in sones and those found through the use of the simple metrics of peak, peak-to-peak and RMS, as the ordering of balls yields the same
results for all methods used. However the difference between the lowest and highest value of Zwicker loudness, measured over the first 10ms of impact, is approximately 6 sones, which is a larger difference to that found using the previous metrics and is significant at the 5% level. Similarly, those values obtained in acum for the sharpness display comparable results to those obtained through the calculation of the centroid of the spectrum. Each of the metrics calculated will be used to examine correlations with the subjective data in the following chapter.

7.1.2. Study of ball sound spectra
Spectra were presented earlier in the analysis that allowed discrimination to be made between balls, for impacts on a hard surface in a laboratory environment. Figures 7.5a-b display spectra obtained for a single player for all balls used, for frequency ranges of 0-10kHz and 0-3kHz respectively. Clearly additional noise is present in the data in terms of background, player and racket noise. In order to determine the frequency components of the sound contributed by the racket, an analysis of the vibration spectrum of the racket, obtained from the mounted accelerometer, is presented in Figure 7.5c for a frequency range of 0-3kHz. It is apparent that the two longitudinal modes of the racket, as found by the modal analysis experiment, the results of which were presented in Chapter 5, at approximately 127Hz and 327Hz dominate the vibration spectrum. In comparison with the sound spectrum in Figure 7.5b, as the spectrum is complex, it is difficult to identify those peaks which are contributed by the racket. As the sound frequency spectrum has been A-weighted the effect of the dominant modes of the racket has been reduced. However those trends found in Figure 7.1 for the balls dropped onto a hard surface are still evident in the real playing scenario. The Tretorn ball still rises to a peak at approximately 1300Hz, though less sharply defined, with the Absorber and Slazenger peaking earlier at around 900Hz. The two other modes of the Absorber and Slazenger identified in Figure 7.1 at approximately 1100Hz and 1300Hz are still evident but their magnitudes have been reduced. The Precision rises to a peak at approximately 1000Hz and then reduces in magnitude but at a slower rate than either the Absorber or Slazenger. It is also apparent from Figure 7.5a-b that the Precision contains higher magnitudes around 2500Hz and above. This is likely the cause of the higher centroid of spectrum and sharpness values. In section 7.1 it was highlighted that the higher frequency modes may not be excited when the impact was on a racket as opposed to a
hard surface. Whilst this appears in some extent to be true, with the amplitudes being reduced for frequencies in excess of 1kHz, the modes are still being excited, and appear to make a large contribution to the overall sound.

The natural frequencies of the balls determined in Chapter 2 at approximately 200Hz appear to contribute little to the sound frequency spectrums as they have been significantly reduced with the applied A-weighting. As the balls display the greatest differences between the values of 750Hz and 2000Hz, it is likely that such frequencies have a large bearing on the perceived sound of the ball.

7.2. Hand/arm vibration objective analysis
Analysis of the vibration data proceeded in a similar manner to that of the sound data. Hence, data was removed that had been corrupted either through players’ mishits or through equipment overloads. In total, 945 ‘good’ shots were used in the analysis out of a total of 1008 total recorded volley impacts. This decrease in the number of shots removed compared to the sound experiment was largely due to the reduced number of mishits caused by the players. Again, checks were made as to the consistency of the data, through graphical analysis. Figure 7.6a-e displays sample acceleration measurements taken at each measurement location, at the grip (X1 and X2), knuckle (X3), wrist (X4) and elbow (X5) respectively.

Three objective metrics were chosen that may correlate with the players’ perceptions of the vibration.

i. Peak-to-peak vibration level (g)
ii. Root mean square (RMS) (g)
iii. Dynamic root mean square (DRMS) (g) – The standard deviation of the trace. Analogous to the root-mean-square of the trace with the mean value of the trace subtracted for each point. This method will remove any dc ‘noise’ from the trace.

The RMS is the generally adopted method of quantifying the severity of human exposures to vibration, though according to Griffin (1990) this preference is not based on any fundamental reasoning that RMS measures of acceleration should predict any
human responses more accurately than any other method. The prime justification is the convenience of measuring and analysis and the widespread use of the technique across other areas of engineering. The two general methods, peak-to-peak and RMS/DRMS often show the same general trends, although having different numerical values (Griffin, 1990). The major drawback of using peak-to-peak measurements is that the measurements are based only on two points rather than the whole measurement.

Each of the three metrics were calculated for every shot used in the analysis. It is unlikely that the players are able to determine the difference in vibration direction at the grip and hence it is probable that the players’ perceptions are based on the overall vibration level at the grip. Roberts (2002) found that the strongest correlations between subjective and objective measurements for golfers were obtained from combined grip vibration measurements. A combined value of acceleration at the grip can be found simply though the use of Eq. 7.3.

\[ \Psi_{DRMS} = \sqrt{X_{1,DRMS}^2 + X_{2,DRMS}^2} \]  

Eq. 7.3

An average vibration value was then calculated for each player for all balls used for each measurement location. The resulting analyses for the combined DRMS measurements of the grip are displayed in Figure 7.7 for each player. It is apparent from Figure 7.7 that, as with the sound experiment, large differences are present between players. The differences between players at the grip are primarily due to the grip adopted by the players at the point of impact, as the impact speed and location of the impact were nominally identical. Variations in the transmissibility between the grip and the hand/arm are likely to be caused by numerous factors unique to each player such as their weight, sex and bone densities which were not recorded for this analysis.

The values from all players were then combined for each of the balls used in the analysis. Tables 7.9a-b outline the results of this analysis for the peak-to-peak and DRMS for all measurement locations. It was found that values of RMS were very
similar to values of DRMS with only a slight effect of noise in the measurements. Therefore only the DRMS is considered for the remainder of the analysis.

<table>
<thead>
<tr>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRMS</td>
<td>Peak-to-peak</td>
<td>DRMS</td>
<td>Peak-to-peak</td>
<td>DRMS</td>
</tr>
<tr>
<td>Absorber</td>
<td>164.98</td>
<td>45.24</td>
<td>121.97</td>
<td>43.87</td>
</tr>
<tr>
<td>Precision</td>
<td>161.74</td>
<td>47.72</td>
<td>112.43</td>
<td>36.08</td>
</tr>
<tr>
<td>Slazenger</td>
<td>175.48</td>
<td>46.92</td>
<td>122.30</td>
<td>46.68</td>
</tr>
<tr>
<td>Tretorn</td>
<td>181.20</td>
<td>47.87</td>
<td>123.33</td>
<td>49.32</td>
</tr>
</tbody>
</table>

Table 7.9a Peak-to-peak values for each ball

<table>
<thead>
<tr>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRMS</td>
<td>Peak-to-peak</td>
<td>DRMS</td>
<td>Peak-to-peak</td>
<td>DRMS</td>
</tr>
<tr>
<td>Absorber</td>
<td>12.69</td>
<td>4.78</td>
<td>8.73</td>
<td>4.01</td>
</tr>
<tr>
<td>Precision</td>
<td>12.52</td>
<td>4.75</td>
<td>8.00</td>
<td>3.06</td>
</tr>
<tr>
<td>Slazenger</td>
<td>13.69</td>
<td>4.83</td>
<td>8.80</td>
<td>3.69</td>
</tr>
<tr>
<td>Tretorn</td>
<td>14.44</td>
<td>4.83</td>
<td>9.43</td>
<td>4.44</td>
</tr>
</tbody>
</table>

Table 7.9b DRMS values for each ball

It is apparent that the trends obtained by the two methods of peak-to-peak and DRMS are the same, with the ordering of balls remaining constant throughout. There is a marked decrease in the amplitudes of vibration between measurement locations. There is a reduction in DRMS values of approximately 22% between the grip and the knuckle. The reduction in DRMS values between the grip and wrist is approximately 55%, with the reduction between the grip and elbow being approximately 90%. A reduction of 4.2 times was found between the wrist and elbow, which agrees very closely with that found in Hennig et al. (1992) at 4.5 times for central impacts.

The highest values of vibration at all locations are the result of the Tretorn ball, with the Precision yielding the lowest values. As the Precision ball is larger in diameter than the other balls, there may be a reduction in impact speed due to the increased
drag of the ball during flight in addition to a reduction of the ball velocity exciting the ball launcher. However the impact speeds were not recorded and hence this cannot be verified.

Again, as with the sound experiment, those differences found between balls are small, with a maximal difference at the grip of 2.5g compared to just 0.7g at the elbow. Hence it is of interest to know whether each of these results are statistically significant, and so a one-way ANOVA was completed with the resulting p-values presented in Table 7.10a-b.

<table>
<thead>
<tr>
<th></th>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.55</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 7.10a One-way ANOVA of peak-to-peak measurements

<table>
<thead>
<tr>
<th></th>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
<th>Grip Combined - Ψ</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 7.10b One-way ANOVA of DRMS measurements

From analysis of Table 7.10a it is clear that there are significant differences at the 5% level for measurements at X1, X2 and X3, whilst for X4 and X5 the results are not significant. This may highlight the weakness of using peak-to-peak measurements in the analysis due to basing the result on two points. In Table 7.10b all results are significant, though X4 and X5 are once again the least significant. There is therefore a clear benefit from using the DRMS to interpret the results.

It was shown previously that normalisation of each player's data can improve significance levels and hence a similar analysis was completed for the vibration measurements, with the results for peak-to-peak and DRMS presented in Tables 7.11a-b.
Table 7.11a Normalised Peak-to-peak values for each ball

<table>
<thead>
<tr>
<th></th>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>-0.19</td>
<td>0.93</td>
<td>-0.03</td>
<td>1.03</td>
<td>-0.18</td>
</tr>
<tr>
<td>Precision</td>
<td>-0.21</td>
<td>0.94</td>
<td>-0.27</td>
<td>0.87</td>
<td>-0.19</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.10</td>
<td>0.99</td>
<td>0.03</td>
<td>0.92</td>
<td>0.08</td>
</tr>
<tr>
<td>Tretom</td>
<td>0.30</td>
<td>1.03</td>
<td>0.28</td>
<td>1.07</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 7.11b Normalised DRMS values for each ball

<table>
<thead>
<tr>
<th></th>
<th>Grip Combined - $\Psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>-0.15</td>
</tr>
<tr>
<td>Precision</td>
<td>-0.26</td>
</tr>
<tr>
<td>Slazenger</td>
<td>0.09</td>
</tr>
<tr>
<td>Tretom</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Whilst the ordering of the balls remains the same, a study of the ANOVA displayed in Tables 7.12a-b once again displays the benefits of normalising the data in terms of increasing the statistical significance of the results.

Table 7.12a One-way ANOVA of peak-to-peak measurements

<table>
<thead>
<tr>
<th></th>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.29</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 7.12b One-way ANOVA of DRMS measurements

<table>
<thead>
<tr>
<th></th>
<th>X1 (Grip)</th>
<th>X2 (Grip)</th>
<th>X3 (Knuckle)</th>
<th>X4 (Wrist)</th>
<th>X5 (Elbow)</th>
<th>Grip Combined - $\Psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

For the peak-to-peak values, X4 and X5 remain insignificant at the 5% level but there has been a reduction in the $p$-value. Both X4 and X5 have significant $p$-values at the
5% level when the DRMS value is used. Although not clear from Tables 7.12a-b all of the p-values have decreased further.

As has been discussed in Chapter 4, the perception and effect of vibration is frequency dependent. Therefore a study of the resulting frequency spectra for each ball may provide additional information. Figure 7.8a-e displays averaged frequency spectra obtained for a single player for all measurement locations. Each spectrum for each ball is comprised of an average of 12 shots. The spectra are highly consistent for each ball, with coincident peaks. Therefore, in terms of producing a metric that enables discrimination between balls, it is unlikely that frequency weighting would have any effect, as all balls would be scaled proportionally. From analysis of the tennis racket vibration properties, provided by the modal analysis experiment in Table 4.6, it is clear that the frequency components of the vibration are dominated by the natural frequencies of the racket. Thus, if rackets were the focus of the study frequency weighting may well yield positive results.

There are clear differences between the frequency content at the grip and that present in the arm. The grip clearly has higher frequency vibrations present from the higher modes of racket and strings. However, these frequencies are not transmitted to the wrist and elbow. This is in agreement with Reynolds & Angevine (1977) who found that, for frequencies above 100Hz, vibration is not transmitted to the arm and is localised to the fingers.

As discussed in section 4.2.3, there is some disagreement in the literature as to whether the vibration of the ball has any impact on tennis elbow. According to the weightings in ISO 5349-1:2001 for injuries caused by hand-transmitted vibration, displayed in Figure 4.18, the weighting applied reduces with frequencies above approximately 10Hz. Through the application of the ISO 5349-1:2001 weightings to values at the elbow, which are dominated by a single frequency component of approximately 150Hz, reduces vibration levels of the balls to the order of 0.2g. However it is not clear what vibration level, if any, becomes significant for the development of tennis elbow. In addition, such frequency weightings have been primarily developed for the assessment of vascular injury prevention, such as vibration white finger. As it has been shown that the vibration transmitted to the arm
of the player is a function of the natural frequency of the racket, it is anticipated that changing to a racket with a higher natural frequency may yield better results, in terms of reducing vibration level, than changing balls. Though statistical differences have been found during the analysis, it is apparent that all balls fall within approximately ±5% of the mean value of vibration for all balls.
CHAPTER 8

Relationships between Subjective and Objective Data

This chapter outlines the correlations found between the subjective data outlined in Chapter 6, with the objective data obtained through all of the experiments completed in the research study.

8.1. Correlation between subjective perceptions and sound metrics

In Chapter 7, a number of metrics were presented to estimate loudness, pitch and duration. For the correlations, normalised objective values of loudness are represented by the RMS (10ms) and the Zwicker loudness, as these were found to be the most significant loudness metrics. Similarly, the duration of the ball sound is represented by the normalised time to drop 25dB from its peak. Finally, for the objective measurement of pitch, normalised values of the centroid of the spectrum and sharpness were chosen.

Each of the objective metrics were correlated with the Bradley Terry values for all sound subjective questions, for all players, as given in Table 6.6. The resulting analysis, which presents the Pearson correlation coefficient (r) of each set of values, is displayed in Table 8.1. Due to there being only four balls used in the analysis, the value of r required to be significant at the 5% level is ±0.95, and correspondingly at the 10% level a value of ±0.90. Those values that are significant at the 5% and 10% level are indicated in Table 8.1 by bold and italicised text respectively.
Table 8.1: Subjective perception correlation with sound metrics for all players

Significant correlations are found at the 5% level between the perceived pleasantness and sound duration, with shorter duration sounds producing negative perceptions of pleasantness. In addition, pleasantness correlates at the 10% level with both metrics of pitch, with a higher pitch ball also producing negative perceptions of pleasantness. Values of hardness and heaviness are not found to significantly correlate with any of the measured metrics. The perceived loudness correlates strongly at the 5% significance level with both loudness metrics of RMS (10ms) and Zwicker loudness, with the perception of a louder ball correlating with higher values of both metrics. No correlation is found between the perceived sound duration and any metrics, and in particular, with the objective metric to measure sound decay, that being the duration of the sound to drop 25dB from its peak. In addition, the perceived speed is not significantly correlated with any of the sound metrics. Finally, the level of control is found to be strongly correlated with both metrics of the loudness of sound, with both found to be significant at the 5% level.

In Chapter 6 it was shown that results were improved through the use of only those players who were deemed reliable. Table 8.2 outlines correlations between subjective and objective sound data only from those players who were deemed reliable as outlined in Chapter 6, whose Bradley Terry merit values are provided in Table 6.10.
A comparison with Table 8.1 of significant values indicates that all values that were significant at the 10% level remain so, with the majority increasing in significance. Only the correlation between RMS (10ms) and perceived control displays a very small decrease in significance. In addition, the centroid of spectrum is found to be significant at the 10% level with the perceived loudness, with a subjectively louder ball having a higher centroid of frequency.

Table 8.1 and 8.2 display significant correlations between pleasantness and the duration of ball sound and frequency content. Whilst not significant, there are also strong trends between pleasantness and the objective loudness, indicating that a sound that is short in duration, high pitched and loud produces negative perceptions of pleasantness.

It was found from the consistency analysis of the perceptions outlined in Chapter 6, that players had difficulty in distinguishing the duration of the ball sound, with no statistically significant differences found between balls when all players were included in the analysis. In addition, no significant values were found between the subjective and objective data. This indicates that players are unable to determine differences in ball sound duration.

As outlined in Chapter 6, players reliably determined differences in ball loudness, with statistical differences found between balls. In addition, perceived loudness is also found to correlate at the 5% level with both the objective metrics of loudness.
This provides strong evidence that players can accurately determine ball loudness and a measure of this can be made through the SPL. Similarly, the perceived level of control correlates strongly with both loudness metrics, indicating that a ball with a loud sound will be perceived as a ball with low controllability.

The speed of the ball off the racket face was also consistency perceived (Chapter 6), although no correlations could be found with any of the sound data. Similarly, weight and hardness, whilst consistently perceived, neither have correlations with any of the objective sound metrics. This indicates that these factors may be primarily perceived by non-sound related factors.

The pitch of the ball sound is of particular interest, as this was consistently determined by the players. However, despite expecting there to be a correlation between perceived pitch and the objective metrics of the centroid of spectrum and sharpness, none was found. There is however, a strong correlation between pitch and the objective metrics of loudness. Upon analysis of the subjective perceptions, it is the Precision ball that is perceived to be 'low pitched' yet is measured objectively to have the highest values of centroid of spectrum and sharpness. Whilst it may be the case that the players are making their assessment of frequency on factors such as loudness, the questioning used for the determination of this perception may be misleading. In assessing pitch, words were used to aid the perception as outlined in Chapter 5, which were 'dull' or 'flat' to indicate a low pitch sound, and 'crisp' for a higher pitch sound. Whilst it is acknowledged that these are words used to describe the pitch of the sound, they may be generic terms that can be applied to the ball as a whole. Due to the size, slowness and overall 'feel' of the larger ball for the serve, this may have contributed to the ball rated as 'dull or flat', which may not be a direct reference to the ball sound. Hence this may indicate that players rate the ball as 'dull' or 'flat' but not necessarily lower pitched.

8.2. Correlation between subjective perceptions and vibration metrics

For the correlation, objective measurements of vibration are represented by the DRMS values found at the grip as, whilst trends between measurement locations are similar, the highest significance of results were obtained at the grip. The results of the Pearson correlation coefficients between the subjective and objective metrics of
vibration are outlined in Tables 8.3a-c. Correlations are presented for all players for perceptions obtained ‘with sound’, ‘without sound’ and the combined results, the Bradley Terry merit values for which are displayed in Tables 6.14a-c. Significant results at 5% and 10% are indicated in bold and italicised text where appropriate.

<table>
<thead>
<tr>
<th>Grip DRMS</th>
<th>Grip DRMS</th>
<th>Grip DRMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Hard + Soft</td>
<td>- Less Vibration + More Vibration</td>
<td>- Quicker + Slower</td>
</tr>
<tr>
<td>-0.18</td>
<td>0.35</td>
<td>-0.87</td>
</tr>
<tr>
<td>-0.95</td>
<td>0.40</td>
<td>-0.87</td>
</tr>
<tr>
<td>0.28</td>
<td>0.41</td>
<td>-0.85</td>
</tr>
</tbody>
</table>

Table 8.3a-c: Correlations between subjective and objective vibration measurements for a) ‘with sound’ results b) ‘without sound’ results c) combined results

From analysis of Tables 8.3a-c it is apparent that the only statistically significant result, at 10% or greater, is obtained between the hardness of feel and measured vibration, with a perceived harder ball associated with an increased value of vibration. The strength of this correlation is greatest for the data obtained ‘with sound’. This may indicate that the hardness of feel is largely dominated by the vibration but there may be a small effect of sound. There is a strong trend, though not significant at the 10% level, between the perceived speed of ball off the racket and recorded vibration level, with higher vibration levels perceived as faster. None of the remaining factors are significant, including most importantly the perceived level of vibration. Again, on analysis of the subjective data, the cause of this is the Precision ball, which despite yielding the lowest recorded values of vibration is perceived as causing the largest amplitudes of vibration.

As for the sound data, the correlations were recalculated for those players who were deemed reliable, with the resulting analysis outlined in Tables 8.4a-b. The tables indicate two groups of reliable players as outlined in Chapter 6, being those who a) passed both consistency tests and b) passed the consistency test based on the
combined results of the ‘with sound’ and ‘without sound’ tests. The value of \( n \) indicates the number of players used in the analysis.

<table>
<thead>
<tr>
<th></th>
<th>Grip DRMS</th>
<th>Grip DRMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Less Pleasant</td>
<td>-0.86</td>
<td>-0.78</td>
</tr>
<tr>
<td>+ More Pleasant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Hard</td>
<td>-0.89</td>
<td>-0.89</td>
</tr>
<tr>
<td>+ Soft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heavy</td>
<td>-0.98</td>
<td>-0.90</td>
</tr>
<tr>
<td>+ Light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Less Vibration</td>
<td>0.86</td>
<td>0.89</td>
</tr>
<tr>
<td>+ More Vibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Quicker</td>
<td>-0.97</td>
<td>-0.87</td>
</tr>
<tr>
<td>+ Slower</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) \( n=3 \)  
(b) \( n=5 \)

Table 8.4a-b: Correlations between subjective and objective vibration measurements for reliable players (\( n \) indicates number of players used in analysis)

It is evident from Tables 8.4a-b that strong trends exist for each of the factors used in the analysis. In particular, those players who were deemed reliable for both vibration test structures produce statistically significant results at the 5% level for the correlation of the perceived weight of impact and the speed of the ball off the racket with the recorded values of vibration. The correlation between the weight of impact and vibration is greatly improved through the removal of unreliable players, who clearly have difficulty in the perception of ball weight.

In addition, whilst still not significant at the 10% level, there is a much stronger trend between the perceived level of vibration and the objective measurement of vibration. This once again suggests that only certain players have the ability to make fine discriminations between balls. The results for the reliable players indicate that an increase in vibration is strongly correlated with a perception of a decrease in pleasantness, increase in hardness, increase in weight, and an increased perception of speed of the ball off the racket.

Due to the low number of players involved in the analysis, when unreliable players have been removed, coupled with only four balls used in the analysis, drawing statistical conclusions is difficult. Ideally the test would be repeated with a larger number of balls and players.
The results suggest that the factors of loudness and pitch are determined through the ball sound, and the factors of weight, hardness, perceived speed of ball off the racket face and vibration, although influenced by the sound, are primarily determined by the perception of vibration. The perceived pleasantness of the ball is likely to be determined by both sound and vibration in addition to other factors.

8.3. Correlation between subjective perceptions and ball dynamic properties

Whilst subjective perceptions were not obtained during the determination of the ball's dynamic properties, it is of interest to compare the calculated values of stiffness and damping coefficients to those subjective perceptions obtained during the sound and vibration experiments to determine whether any correlations exist. It was shown in the previous section that the strongest correlations were obtained through the use of players deemed reliable. Therefore Table 8.5 displays the correlation between the stiffness and damping coefficients calculated in Chapter 2, using the line of best fit, for an impact at service speed for an elite male player (Chapter 1) and the subjective responses for the reliable players in the sound analysis.

<table>
<thead>
<tr>
<th></th>
<th>Stiffness</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Less Pleasant</td>
<td>0.74</td>
<td>0.13</td>
</tr>
<tr>
<td>+ More pleasant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Hard</td>
<td>0.85</td>
<td>-0.75</td>
</tr>
<tr>
<td>+ Soft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heavy</td>
<td>-0.40</td>
<td>0.95</td>
</tr>
<tr>
<td>+ Light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Higher Pitch</td>
<td>0.87</td>
<td>-0.76</td>
</tr>
<tr>
<td>+ Lower Pitch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Loud</td>
<td>0.99</td>
<td>-0.37</td>
</tr>
<tr>
<td>+ Quiet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Longer duration</td>
<td>-0.13</td>
<td>0.85</td>
</tr>
<tr>
<td>+ Shorter duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Quicker</td>
<td>0.41</td>
<td>-0.75</td>
</tr>
<tr>
<td>+ Slower</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- More control</td>
<td>-0.97</td>
<td>0.59</td>
</tr>
<tr>
<td>+ Less control</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.5: Correlations between sound perceptions and stiffness and damping coefficients for impacts at service speed for reliable players

It is clear from Table 8.5 that there are a number of anomalies in the data. A significant value at the 5% level is found between the perceived weight of the ball and the damping coefficient, indicating that a ball perceived as light is associated with high levels of damping. Throughout the study, the Tretorn ball was perceived to be 'light' despite it possessing the lowest values of stiffness and highest levels of damping at higher velocities, and conversely, the Precision was perceived to be
'heavy' despite having the lowest values of damping. During the analysis of subjective perception, the players appeared to have the greatest difficulty in the assessment of perceived weight. Together with these findings, this indicates that the terms 'heavy' and 'light' are poorly defined by the players, who may interpret the terms in a different manner. The Precision may have been rated as 'heavy' due to its increased size representing an inability of the players to generate any pace in the ball.

In addition, a strong trend exists between the perceived hardness of the ball and the stiffness, with a perceived softer ball having a high level of stiffness. Clearly, this correlation is the opposite of what would be expected, however the players were able to reliably distinguish ball hardness. Again, the Tretorn ball may be highlighted, as whilst being dynamically the least stiff at higher velocities, was perceived to be 'hard'.

The perceived sound properties of loudness, pitch and duration all provide strong correlations with the calculated values of stiffness and damping. There is a statistically significant correlation, at the 5% level, between the perceived loudness and stiffness, with an increase in stiffness associated with a perceived quieter sound. In addition, the perceived pitch of the ball is strongly correlated with the stiffness and damping, with a perceived increased pitch corresponding to lower values of stiffness and higher values of damping, though once again this is opposite to what would be expected. As has been discussed in Chapter 7, it is likely that the association of the high pitch of the Tretorn ball is due to a peak at 1300Hz and hence it is not clear whether the correlations with stiffness and damping coefficients are relevant. In addition, the damping correlates strongly with the duration of the ball sound with, as expected, a ball with high damping producing perceived shorter duration sounds.

There is a statistically significant correlation, at the 5% level, between the perceived control and stiffness, with an increase in stiffness associated with a perceived increased level of control. Whilst not significant, the stiffness of the ball is strongly correlated with the pleasantness. This agrees with the anecdotal evidence that a low stiffness ball, such as a depressurised ball, promotes bad ball 'feel'.
This analysis highlights that the stiffness and damping may not be good predictors of all dimensions of ball ‘feel’. It is not clear why, for example, the Tretorn is perceived as ‘hard’, though it may be the influence of other factors, which may include, the ball sound and vibration, the speed of the ball through the air, the ball contact time, or any other factor outlined in Chapter 3.

A similar analysis of the subjective vibration perceptions for reliable players correlated with the stiffness and damping values is presented in Table 8.6. However, dynamic values of stiffness and damping are calculated for volleying speeds, using the ball canon data outlined in Chapter 2. Subjective data is used for those players deemed reliable by passing the combined vibration consistency tests as outlined in Chapter 6.

<table>
<thead>
<tr>
<th></th>
<th>Stiffness</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Less Pleasant</td>
<td>0.58</td>
<td>0.18</td>
</tr>
<tr>
<td>+ More pleasant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Hard</td>
<td>0.10</td>
<td>0.80</td>
</tr>
<tr>
<td>+ Soft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Heavy</td>
<td>0.67</td>
<td>0.57</td>
</tr>
<tr>
<td>+ Light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Less Vibration</td>
<td>-0.05</td>
<td>-0.77</td>
</tr>
<tr>
<td>+ More Vibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Quicker</td>
<td>0.32</td>
<td>0.75</td>
</tr>
<tr>
<td>+ Slower</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.6: Correlations between vibration perceptions and stiffness and damping coefficients for volleying speeds, using subjective data for reliable players

It is apparent from Table 8.6 that there are no significant correlations at the 10% level or greater. Through comparison with Table 8.5, it is clear that the correlations vary largely for similar questions used in both analyses, with trends being much weaker for the vibration perceptions. As has been shown in Chapter 2, the trends of stiffness and damping between balls are heavily dependent on impact speed. In addition, there is a greater difference between stiffness and damping values at higher impact velocities. It would therefore be anticipated that players would have a greater difficulty in distinguishing between balls in the vibration experiment, due to the lower impact speed, and in addition, the balls would be perceived differently. However, where the same questions were used for both tests, similar subjective responses were obtained. This once again suggests that the stiffness and damping alone may not be used to predict ball ‘feel’ and that other factors have a large influence.
CHAPTER 9

Recommendations for Further Work

9.1 Investigation of other dimensions

Eight general dimensions emerged from the study of players' perceptions of a tennis ball but only two have been investigated in detail during this research project, namely the general dimensions 'sound' and 'feeling from impact' and their associated inter-dimensional relationship. Other dimensions are worthy of further investigation, including the numerous inter-dimensional relationships, because it has been shown that differences between balls associated with the dimensions studied are small. It is likely therefore that the remaining dimensions have a significant effect on the overall perception of the ball. The general dimension 'wear' has a large bearing on a number of other dimensions and can change the 'feel' of the ball over time. For example, a ball may be perceived as 'heavier' due to excessive cloth 'fluffing', while the sound and vibration produced by the ball is likely to be unaffected by this change in condition.

The approach used in this study to produce the tennis ball 'feel' map through open-ended interviews, inductive analysis and structured relationship modelling may also be replicated to elicit perceptions of different tennis equipment such as strings, rackets or courts, equipment used in other sports, alternative groups of performers or even applied outside sport. The procedure highlights the success with which information may be gathered during play from elite performers, allowing their perceptions to be elicited as they arise and not in retrospect. In this study the ability to interview the players whilst playing with a wide variety of balls certainly increased the quantity and quality of information gathered.
Whilst the 'feel' map says nothing about the relative importance of each dimension it would be possible to combine the information obtained during the perception study and from the online questionnaire to form a three-dimensional map, highlighting both the dimensions, inter-dimensional relationships as well as their relative importance.

Once dimensions of 'feel' have been established, the test methodology successfully developed during this study of capturing synchronous subjective and objective data, may also be applied to furthering the understanding of each dimension. The method of paired comparisons allows the elicitation of players' perceptions even when only small differences are present as well as evaluation of their reliability as test subjects.

9.2 Improvements to test structure
This study has obtained data that displays strong correlations between the subjective and objective data, but to enable complete confidence in the results obtained, a greater sample size would be necessary. The results obtained during the study may be validated through the use of a different set of balls, through varying the shot selection or through the use of different players.

The technique of removing players deemed unreliable proved successful in improving both the significance of the results as well as improving the correlations between the subjective and objective data. However, as a large number of players were removed, from the vibration testing in particular, it is suggested that for any future tests an 'elite testers' group of players are established that are able to report their perceptions reliably. This could be demonstrated through the completion of a paired comparison experiment and subsequent consistency analysis, which would allow suitable players to be identified. If this pool of players were used regularly, their greater experience in participating in these types of test may also improve their performance in the test.

An experiment protocol is required to determine the optimum number of testers required for significant results to be obtained for studies of this nature. In addition, the ideal number of shots required during tests for players to be able to report their perceptions accurately is currently unclear. It is suggested that a minimum shot type strategy for ball evaluation is developed. Determining the minimum number of shots
required would either increase the quality of the results obtained or allow more balls to be evaluated during an allocated time period without fatigue becoming a factor.

Further improvements are required for on-court measurements. Throughout the analysis, the players were attached by means of fixed wires to the recording equipment. Whilst this technique can be adequately performed for shots that involve limited translational movement such as the serve and net punch volley, it would not be applicable for measurements in a real game scenario. A wireless instrumented racket would allow freedom of movement for players and hence allow additional shots to be recorded. The service and volley stroke used in this study only partially make up a tennis player’s repertoire. Differing perceptions were obtained in this study through the use of the two shot types. Whilst the changes in test structures may account for a proportion of these changes in perception it is likely that the ‘feel’ of the ball is different for varying shot types. Ideally data from a wireless instrumented racket would be stored for later analysis, hence allowing whole games to be analysed. In addition the instrumentation developed would have to not adversely affect the ‘feel’ of the racket else the perceptions obtained may be dominated by the racket and not the ball.

Ideally all future testing would be conducted blind. This would necessitate all logos to be removed as the effect of blanking them through a blacked rectangle, which is the traditional way of removing logos, affects the visibility of the balls and disturbs the players.

As a number of dimensions are linked via inter-dimensional relationships it is difficult to assess one dimension without the effect of another. It has been shown in this study that through the removal of sound the players’ ability to distinguish differences between balls was decreased. Therefore suitable experiments should be designed so as to isolate the dimensions of interest. For example, studying the effect of ball sound through the modifying of internal pressures and gasses, so as to keep the ball characteristics the same with the exception of the ball sound.
9.3 Development of single-degree-of-freedom model

As has been discussed in Chapter 2, the SDOF ball model, which was used to characterise the balls in terms of stiffness and damping coefficients, underestimates the contact time of the impact. This has been shown to be due to the extension of the back of the ball, which continues to remain in contact with the surface, as the front of the ball moves away from the surface. This phenomenon can be seen in Figure 9.1, which displays a HSV image of a Slazenger ball at 40m/s, showing a clear deformation of both front and back portions of the ball. Whilst the SDOF model provides a reasonable fit to the experimental data, it cannot accommodate such deformations. Therefore there is a requirement for a model that can both predict the contact time accurately but also that models the deformation of the ball throughout impact.

Those developments of the SDOF model made by other researchers, for example Goodwill & Haake (2004), have concentrated on improving the fit of the SDOF model. In the case of Goodwill & Haake (2004), the improvement in fit was primarily obtained through varying the stiffness and damping coefficient of the ball during impact. Whilst improving the standard fit to the experimental data they fail to accommodate the deformation of the ball adequately, only modelling the displacement of the centre of mass.

Through the use of a 3DOF model, it is anticipated that the fit to the data can be improved and that the deformations of the front and back of the ball can be predicted. A proposed model is displayed in Figure 9.2, which is modelled as three discrete masses representing the front and back of the ball together with a central mass. The two additional masses of the ball, which represent the front and back portions, are connected to the central mass via means of a spring and damper in parallel of coefficients $k_b$ and $c_b$ respectively. A massless interface is added to replicate the effect of the ball cover during impact and connected to the ball by a spring and damper in parallel of coefficients $k_0$ and $c_0$ respectively. The total mass of the ball is given by $m$. Each additional mass is assigned an equal mass of $am$ hence resulting in the central mass being $(1-2\alpha)m$. Such a 3DOF model allows prediction of the displacement, velocity and acceleration of each of the three parts of the ball during impact.
Equating the forces on each mass of the ball model yields the matrix displayed in Eq. 9.1. Hence through knowledge of values of $\alpha$, $m$, $k_b$ and $c_b$ it is possible to predict values of $F_b$ throughout impact.

\[
\begin{bmatrix}
am & 0 & 0 \\
0 & (1-2\alpha)m & 0 \\
0 & 0 & am
\end{bmatrix}
\begin{bmatrix}
\ddot{x}_1 \\
\ddot{x}_2 \\
\ddot{x}_3
\end{bmatrix}
+
\begin{bmatrix}
c_b & -c_b & 0 \\
-c_b & 2c_b & -c_b \\
0 & -c_b & c_b
\end{bmatrix}
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix}
+
\begin{bmatrix}
k_b & -k_b & 0 \\
-k_b & 2k_b & -k_b \\
0 & -k_b & k_b
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3
\end{bmatrix}
=
\begin{bmatrix}
-F_b \\
0 \\
0
\end{bmatrix}
\]

Eq. 9.1

In addition equating forces for the cover yields an alternative method for the calculation of $F_b$ as shown in Eq. 9.2.

\[
F_b = -k_c[y-x] - c_c[y-x]
\]  

Eq. 9.2.

In a similar manner to that detailed in Chapter 2, the central difference method may be used to determine the derivatives of $x(i)$. Hence, given initial values of stiffness and damping from the fit of the SDOF model and through an estimation of $\alpha$, values of $F_b$ may be calculated, which can be compared to the experimental data. The stiffness and damping parameters along with the mass ratio $\alpha$, may then be refined until the optimum fit is achieved between the model and the experimental data. The solution will provide best fit values for the cover stiffness and damping, ball stiffness and damping and mass ratio.

The value of $\alpha$, that is the proportion of mass assigned to the top and bottom of the ball, is likely to be dependent on the impact velocity. Higher velocities result in larger deformations of both top and bottom of the ball and hence increased proportions of the mass should be placed in the external masses. Whilst such a model may adjust the value of $\alpha$ so that the optimum fit is achieved, if the measurements of the deflections of each ball were calculated at each impact velocity, via means of video footage, it may be possible to determine an empirical solution to $\alpha$ based on impact velocity and ball type.
This model requires development so as to predict the ball impact accurately but the work completed to-date highlights the potential benefits of such a model.
The aim of this study was to develop a comprehensive understanding of the characteristics that contribute to a player's perception of 'feel' of a tennis ball and in addition to investigate the suitability of various test procedures and data analysis methods for studies of this nature.

The six balls evaluated in the study, chosen for their differing properties, were the Dunlop Absorber, Dunlop Fort Plus, Dunlop Precision, Slazenger Wimbledon, Tretorn TXT and Wilson US Open.

A series of interviews were completed with elite tennis players to determine their perception of 'feel' of a tennis ball. The balls were evaluated during a series of 5-minute structured sessions incorporating the players' full range of strokes. An open-ended questioning style was used to elicit the players' perceptions using elaboration probes where necessary. The resulting interviews were transcribed and following an inductive analysis of the transcripts a comprehensive 'feel' map was produced highlighting all dimensions that contribute to the overall 'feel' of a tennis ball and any associated links between them. In total, eight dimensions of 'feel' were found together with twelve inter-dimensional relationships.

An online questionnaire was created and circulated to a wider group of tennis players of all abilities. The questionnaire identified ideal 'feel' characteristics for each of the dimensions found during the perception study as well as determining the relative importance of each of the dimensions. The results indicate that the ability to control
the ball both in the air and on the racket, as well as the consistency of the bounce are most important to the players.

The dimensions of 'feeling from impact' and 'sound' and their associated inter-dimensional link were chosen to be further evaluated through a set of mechanical and play tests.

A series of impact tests were completed using an instrumented force plate to characterise the mechanical properties of the balls. A single-degree-of-freedom viscoelastic ball model was developed and through the use of numerical integration, values of stiffness and damping, peak force and contact time were reported for impact velocities of 16-66m/s, which include the speeds found at the upper echelons of the male game for which data has not previously been reported. A data correction method was determined to calculate the true force acting on the force transducer, eliminating the effect of the movement of the front plate on the measured output. The effect of this correction was to both increase the measured force and to alter the shape of the force profile, with a more clearly defined initial peak.

Whilst differences between balls were small for those velocities used for the ITF ball regulation testing, the differences between balls were exaggerated for higher impact velocities. For an elite male service velocity of approximately 50m/s, differences in stiffness were approximately 24% or 35.5kN/m between the pressureless Tretorn, yielding the lowest values of stiffness, and the pressurised Fort Plus, yielding the highest values of stiffness. Damping values at this speed differed by 14.6% or 11.2Nm/s between the oversize Precision, which yielded the lowest values of damping and the pressureless Tretorn, which yielded the highest values of damping. Values of peak force yielded the smallest variation between balls with the largest differences being just 12.9% or 635N between the pressureless Tretorn yielding the highest value of peak force and the Wilson US Open, yielding the lowest values of peak force at 50m/s. All balls displayed a similar trend of decreasing contact time with an increase in ball speed with typical contact times of 4ms for an impact at 15m/s to 2ms at a speed of 55m/s.
The correlation between the dynamic stiffness and damping data with subjective perceptions obtained during the study produced a number of anomalies, which highlights that stiffness and damping alone may not be directly used to predict ball ‘feel’.

A further series of impact experiments were completed for oblique impact angles from 15° to 75° incorporating velocities from 16-66m/s. For oblique impacts, the normal component of force was found to be independent of impact angle and only dependent on the normal component of velocity. Tangential forces are governed by the interaction between the ball and the surface and are dependent on the normal velocity, impact angle and sliding velocity.

A modal analysis experiment was completed that determined the first natural frequencies of each of the balls used in the study, which ranged from 190-250Hz. As for the ITF quasi-static tests that define the limits of the ball’s static properties, the natural frequencies of the balls acquired in this way cannot be used as a predictor of how the balls will behave in high speed impacts. At higher speeds, variations in stiffness between balls are up to ten times those found for such quasi-static tests.

Two separate experiments were completed into the sound and vibration at impact, both capturing synchronous subjective perceptions and objective data in a realistic tennis playing environment. Two separate test structures were designed to maximise the quality of the captured data.

In the sound experiment a service stroke was chosen so as the impact speed and hence impact sound would be at its maximum and also did not require the ball to be delivered prior to impact. In order to identify the contribution of the racket sound in the sound frequency spectra an accelerometer was attached to the throat of the racket so that the frequency components of the racket contributing to the sound could be identified. Furthermore, a modal analysis experiment was completed on the racket in order to determine its natural frequencies.

In the vibration experiment a backhand punch volley was employed, with the ball delivered via a ball launcher, in order that the players required limited lateral
movement to perform the shot due to the equipment restricting their movement. Instrumentation was developed that allowed the measurement of vibration directly at the grip and on the hand/arm of the players. An adaptor was produced that was held directly between the hand and racket handle. The use of thin card and adhesive tape proved successful in the attachment of the accelerometers and subsequent measurement of the vibration levels at the knuckle, wrist and elbow of the players. Through the use of ear defenders it was possible to determine the effect of sound on the players' perceptions of vibration by removing sound from the impact.

The paired comparisons method of obtaining subjective perceptions proved successful in the assessment of subjective ball characteristics. The Bradley-Terry model was used to transform the paired comparison data into scaled data such that it could be represented on a linear scale. In addition, this method allowed a consistency test to be developed that resulted in the reliability of players being evaluated through analysis of their responses. A scoring system was devised dependent on the number of contradictions in the players' responses, such that a statistical cut-off could be applied, where if a player scored over a threshold they could be assumed to be an unreliable judge. This system was first developed for one question, with the model developed to allow multiple questions to be analysed. Through the removal of players deemed unreliable, the fit of the model used to transform the paired comparison results to scaled data was improved, there were exaggerated differences between balls and the significance of the results was increased.

Subjectively, players perceived a harder ball to be louder, faster off the racket, and possess a sound that was higher in pitch and shorter in duration. In addition, a ball perceived as heavy was perceived to produce a longer duration sound and to be slower off the racket. There was also a perceived loss of control for balls with sounds that were perceived to be louder and higher in pitch. Balls perceived as causing low levels of vibration were perceived to be pleasant, softer and lighter. It was found that the player's ability to distinguish between balls was diminished when sound was removed from the impact with decreased differences between balls and in general a decrease in consistency of responses.
Objective sound metrics were determined to correlate with the subjective data. Close agreement was achieved between the ‘raw’ metrics such as the peak-to-peak sound level, RMS SPL and the centroid of the frequency spectrum and the psychoacoustics metrics of Zwicker loudness and sharpness. The sound of impact was found to be concentrated in the first 10ms after impact and it was over this data length that significant differences between balls were found. Analysis of only the first 10ms of impact removed undesirable noise such as the player landing on the court or reflections from the court and walls of the tennis centre. The sound spectra for each of the balls used in the experiment were measurably different, with the most significant differences in excess of 1kHz, particularly for the Tretorn ball, which was found to have a distinctive peak at 1300Hz.

There were large differences in the measured values of vibration between players, which may be attributed to the style of grip adopted as all other factors such as impact speed and impact location were nominally identical. Due to this intersubject variability, the most significant results were found between balls through normalising each player’s data, hence ensuring all players had the same mean, so any variability between players was removed. The level of vibration transmitted to the player was statistically different for all balls, though these differences only varied by ± 5% from the mean for all balls. Whilst higher modes of vibration of the racket were present at the grip, only vibration frequencies up to the first natural frequency of the racket were transmitted into the hand/arm. Dynamic RMS values of acceleration at the knuckle were 78% of that found at the grip. These values were further reduced to 45% of the grip acceleration at the wrist and only 10% at the elbow. The benefit of using the dynamic RMS values of acceleration for the entire data length was highlighted, as opposed to peak-to-peak measurements, as displayed by an increased significance of results.

Significant correlations between the subjective and objective metrics were found between the perceived loudness of ball sound and the SPL and Zwicker loudness for the first 10ms of impact. No correlations were found between the perceived pitch of ball sound and the measurement of frequency content, or the perceived sound duration and any metric of decay. Balls that had a shorter duration, were high pitched and had a loud sound were perceived as unpleasant.
The strongest correlations between the subjective data and objective metrics were obtained for those players deemed reliable, highlighting that only skilled test subjects are capable of such fine discriminations between balls. Results from players deemed reliable indicate an increase in vibration level is associated with a perceived decrease in pleasantness, perceived increase in hardness and weight as well as an increased perception of speed off the racket face.

This study has successfully developed techniques to elicit and quantify players’ perceptions and has developed test structures to measure objective data representative of the feedback received by the players from impact during actual play conditions.
References


Kistler Cutting Force Measurements. *Innovative Precision for optimising productivity*. Winterthur, Switzerland, Kistler Instruments Ltd.


Ball Type 3
High bouncing
Slower ball

Ball Type 2
Medium bouncing
Traditional ball

Ball Type 1
Low bouncing
Faster ball

Ball incoming
trajectory

Figure 1.1: Ball type classification (adapted from Coe, 2000)

Figure 1.2: Prediction of ball 'feel' from ball dynamic properties.
Arrow indicates increasing 'good feel' (Haake et al., 2003).
Figure 2.1: Dynamic COR against incoming ball speed (adapted from Millar & Messner, 2002)

Figure 2.2: Tennis ball force profile obtained by Cross (2000)

Figure 2.3: Inversion of the contact region (Cross, 1999)
Figure 2.4: Model of viscoelastic impact (Babitsky & Veprik, 1998)

Figure 2.5: Stiffness and damping for various balls (Haake et al., 2003)
Figure 2.6: Viscoelastic impact model fit (Goodwill & Haake, 2004)

Figure 2.7: Viscoelastic impact model fit (Babitsky & Veprik, 1998)

Experimental (---) and analytical (—) time histories of acceleration at viscoelastic impact.
Figure 2.8: Kistler force transducer (Kistler Cutting Force Measurements)

Figure 2.9: Ball cannon adjustable frame
Figure 2.10: Model of a force transducer with additional top and bottom masses (adapted from Kistler Instruments, 2004)

Figure 2.11: Force plate mounted in canon with impact hammer strike, raw force plate output and corrected force plate output
Figure 2.12: Averaged accelerometer output, raw and corrected force plate output for Slazenger ball at 16m/s.

Figure 2.13a Model fit at low velocity (15m/s).
Figure 2.13b: Model fit at medium velocity (30m/s).

Figure 2.13c: Model fit at high velocity (60m/s).
Figure 2.14: Stiffness values for Tretorn ball

Figure 2.15a: Stiffness values for all balls
Figure 2.15b: Damping coefficients for all balls

Figure 2.15c: Peak force values for all balls
Figure 2.15d: Contact times for all balls

Figure 2.16: Comparison of results obtained from this study and that by Haake et al. (2003) also indicating ITF regulations for static stiffness
Figure 2.17: Peak force plotted against stiffness for Fort Plus ball

Figure 2.18a: Force profile indicating high speed image locations
Figure 2.18b: $t=0$ – Start of impact

Figure 2.18c: $t=1$ – Initial rise in force

Figure 2.18d: $t=2$ – Peak force
Figure 2.18e: $t=3$ – Peak deflection

Figure 2.18f: $t=4$ – Gradient change of force profile

Figure 2.18g: $t=5$ – Impact end
Figure 2.18h: \( t=6 \)– Ball after impact showing deformation

Figure 2.19: Comparison of (a) pressurised and (b) pressureless ball impact at high velocity (65m/s)
Figure 2.20: View of contact area for Tretorn ball at 59.67 m/s

Figure 2.21: Oblique force plate angles
Figure 2.22: Averaged accelerometer output, raw and corrected tangential force plate output for Slazenger ball at 25m/s for oblique impact at 15°.

Figure 2.23: Normal peak forces obtained for a Tretorn ball at various oblique angles.
Figure 2.24: Normal component of velocity plotted against normal peak force for Tretorn ball

Figure 2.25: Tangential peak forces obtained for a Tretorn ball at various oblique angles
Figure 2.26a: Normal component of velocity plotted against tangential peak force for Tretorn ball

Figure 2.26b: Tangential component of velocity plotted against tangential peak force for Tretorn ball
Figure 2.27: High speed video image of oblique impact of Slazenger ball at 18m/s

Figure 2.28: Variation in COF (μ) for a Fort Plus ball at 25m/s at an impact angle of 15°. Error bars represent ±25 N variation in either value of tangential or normal force
Figure 2.29 - Tennis ball modal analysis experimental set-up

Figure 2.30 - Sample frequency response function (FRF) of a tennis ball
Figure 2.31 – Mode shape of first natural frequency of an incompressible sphere (Shannon & Axe, 2002)
Figure 3.1: Interview test equipment
<table>
<thead>
<tr>
<th>Example Quotes</th>
<th>Base Themes</th>
<th>High Order Sub-Themes</th>
<th>General Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>It sounded almost flat...</td>
<td>Flat Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It sounded like you were hitting with a flat ball</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It makes a hollow sound, quite off-putting again, I didn't enjoy that</td>
<td>Hollow Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's a hollow sort of sound...</td>
<td>Pop Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's a higher tone of sound, its more of a crisper pop</td>
<td>Echo sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The sound of the ball, the echo, was so distinctive, you couldn't hear anything else</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This ball sounded like an echo when you hit it</td>
<td>Tinny Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>That ball you could really hear a real tinny sound, it was horrible</td>
<td>Dull Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A bit tinny, it sounded a bit tinny</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dull in its sound off the court</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sounded like a dull thud</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's a little bit more like a pingy sort of sound</td>
<td>Pingy Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It makes a ping every time you hit it</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It made a normal sound, I mean it is what you would expect a tennis ball to sound like</td>
<td>Normal sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It just sounded like a tennis ball, a normal sound</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It just sounds hard and bullet like</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unbelievable, I mean I hit that one and I have never heard anything like it, like a clack of a sound</td>
<td>Other Sound Descriptors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The ball is louder so it is like a bullet going off</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A louder, clacking sound</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's quite loud isn't it, I mean it's a real crunch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's one of those pressureless balls so it makes that characteristic ping every time you hit it</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The sound is different. I don't know what it is made of but it sounds different to a pressurised ball</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I think it (the sound) is off-putting if you're playing and you're just not happy with the ball</td>
<td>Distraction of Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's just unpleasant, you can't relax in that environment because of the noise</td>
<td>Effect of Sound</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I mean if you don't hit it off the middle you can hear it in the ball even, it's a different noise</td>
<td>Sound due to Location of Impact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very disconcerting, you hit a ball off centre and you get that loud clack</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2: General Dimension - Ball Sound
<table>
<thead>
<tr>
<th>Example Quotes</th>
<th>Base Themes</th>
<th>High Order Sub-Themes</th>
<th>General Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>It's got a sort of cannon ball feel to it when you hit it. It feels very heavy at the hit.</td>
<td>-</td>
<td>Hardness of feel</td>
<td></td>
</tr>
<tr>
<td>It was really heavy, so you felt like you were having to use your arm to hold it because it's coming through heavier it's knocking the racket back so you have got to really stand up to it</td>
<td>Heavy impact</td>
<td>Weight of impact</td>
<td></td>
</tr>
<tr>
<td>It's quite heavy off the strings</td>
<td>Light impact</td>
<td>Effect of ball type</td>
<td></td>
</tr>
<tr>
<td>It felt light, which meant it felt nice on the racket not too much tension up your arm because it was light</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I found it a very light ball, seemed to be light on the strings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I think they are pressureless so they are very heavy on the strings and it just makes your arm ache</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's obviously a pressureless ball which automatically makes it feel heavier. It feels very heavy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yeah, it was nice to play with, had quite a bit of feel</td>
<td>Feeling ball on racket</td>
<td></td>
<td></td>
</tr>
<tr>
<td>You felt as though you could feel the ball on the racket</td>
<td>High level vibrations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>You can really feel the ball on the strings. It's not coming through the back necessarily but you hold the ball on the strings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It's just like an effort to hit the ball it chings into the strings and vibrates. It sends that shock through the racket into your arm. It's a real chingy kind of feeling in your arm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very very reactive, but very very hard on the strings and on your body and on your arm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>There was much less vibration from this ball, more comfortable to hit with</td>
<td>Low level vibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>You didn't feel any vibrations through the racket through the arm because it felt so light, so it was a nice ball to hit with. They felt quite forgiving, they didn't give much shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If feels really heavy if you don't strike it clean, I mean you can feel vibration through your arm, I can already feel it in my elbow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I would say that the weight of it for off-centre hits will cause vibration up the arm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well if you hit a harder ball you can feel the vibration in your arm slightly because it's a bit harder, especially if you miss time it slightly</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If you hit it outside it was horrible, but if you hit it in the middle then it was nice</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3a: General Dimension - Feeling from Impact
Example Quotes

It has got a tinny feel when you hit it. It's kind of so crisp it's almost a metally, it has a metallic feel to it

It felt very tinny, it was very very hard, it wasn't squishy, it didn't feel like rubber at all

A very crisp ball on the hit

It was a very clean, light crisp kind of feeling off the strings as opposed to more of a heavy plop

A harder ball, you can definitely feel that when you are hitting it. When you contact it, it definitely feels like a harder ball

This ball is just so bloody hard and that's what hurts your arm it's like hitting bricks

These are the hardest of the three, they feel like rocks the whole time

I found them to be hard, very hard. I mean when you hit it, it is very solid it doesn't give much

It felt solid on the hit

It feels very heavy, very much a puddingy feel to it so it's not a hard feel it's a much softer feeling, almost like a pudding. The one thing that sprung to mind was the words Yorkshire pudding

Seemed to feel it really sank in, it quite a puddingy kind of feel

They definitely feel like the softest ball on the racket to be honest

This ball was really soft on the racket, it sort of feels a bit soggy off the racket, like it was squelching

Base Themes

Low Order Sub-Themes

High Order Sub-Themes

Tinny Feel

Crisp feel

Hard feel

Solid feel

Hard impact

Hardness of feel

Puddingy feel

Soft feel

Soft impact

Figure 3.3b: High-Order Sub-Theme - Hardness of feel
It was like playing with a ping pong ball, hard but it flew off.

They are hard so they won't embed themselves in the racket face, they will fly off the racket straight away.

Well there's not much response in the ball you know when you hit it, it’s very solid, it doesn't give much, it feels like a rock.

When you feel the ball on the racket there is not as much give in the ball.

No it doesn't deform as much as the other ball.

This ball you can feel when it grips into the string bed, you can sense that it’s being pushed in, deforming in.

A bit softer than the first ball so you can sort of feel it going in.

It sinks into the strings a lot further.

It stays on the racket longer so you can't hit it as hard.

Because the ball is softer it's not coming off the racket as quickly so you can give it a bit more. It is not reacting off the face like the other one was.

These balls are deforming more so you can't generate the same sort of pace as you could with those last ones.

You just can't get any pace out of these balls when you hit them.

Ball flies off racket face → Lively feel

Ball doesn’t deform → Feeling of ball behaviour

Ball deforms into racket → Dead feel

Ball stays on racket → Cannot generate pace in ball

Figure 3.3c: High-Order Sub-Theme - Feeling of ball behaviour
<table>
<thead>
<tr>
<th>Example Quotes</th>
<th>Base Themes</th>
<th>Low Order Sub-Themes</th>
<th>High Order Sub-Themes</th>
<th>General Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bouncy, very light, and very very bouncy</td>
<td>Bouncy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>They were pretty bouncy off this court</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It generally felt sort of light and springy</td>
<td>Springy</td>
<td></td>
<td>High bounce descriptors</td>
<td></td>
</tr>
<tr>
<td>Well it felt like a typical Tretorn ball, very springy and hard</td>
<td>Reactive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>They were pretty bouncy off the court, they were reacting to the court pretty well</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yeh, it bounced reasonably high, it was quite a lively ball when it bounced</td>
<td>Lively</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I thought this ball was livelier off the court than the first ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It didn't bounce at all really, just skidded straight through</td>
<td>Skidding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Those balls did skid through a bit more</td>
<td>Dead</td>
<td></td>
<td>Low bounce descriptors</td>
<td></td>
</tr>
<tr>
<td>These balls were deader off the court</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I thought they kept quite low</td>
<td>Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It was staying low on the court</td>
<td>High</td>
<td></td>
<td>Hard bounce</td>
<td></td>
</tr>
<tr>
<td>It bounced up quite high because it was a hard ball</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This is a really hard ball, so it bounced high</td>
<td></td>
<td></td>
<td></td>
<td>Effect of compression on bounce</td>
</tr>
<tr>
<td>No it doesn't deform as much as the other ball, which obviously you don't want too much of but I felt as though they were really hard so subsequently the ball, when it come off the court you felt it came off a lot quicker which meant you didn't have as much time</td>
<td>High</td>
<td></td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td>It went quite quickly, and when it hit the ground it really came through quickly</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This ball really flew after the bounce</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It doesn't bounce as high because it is a softer ball</td>
<td>Low</td>
<td></td>
<td>Low bounce</td>
<td></td>
</tr>
<tr>
<td>It was definitely soft on the court so you weren't getting as much bounce</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>It wasn't as high bouncing, it was softer on the court</td>
<td>Slow</td>
<td></td>
<td>Soft bounce</td>
<td></td>
</tr>
<tr>
<td>These are a lot bigger so they are slower through the air and off the court</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Painfully slow, it was very soft off the surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.4a: General Dimension - Bounce (1)
Example Quotes

It's a light ball so it affects the bounce, yeah it is a higher bounce

Those balls were pretty light and bouncy. I think that might have been due to the weight, they were pretty bouncy off the court.

The feeling or sensation I get when it bounces, it is just a sort of steadier heavier bounce, which is lower.

The first one was the heaviest. This is the nearest one being on the bounce, in fact after the second bounce it sort of just dies.

A high bouncing ball but not responsive to spin so if you throw it high in the air it will bounce very high but if you hit heavy top spin it doesn't have any impact on the bounce, that's a very low bounce of a top spin flight path. So, tactically you would be better off playing flat.

Got a nice bounce, you know how it is going to bounce every time.

Every single time you knew it was going to bounce, it was very predictable.

And the bounce of this one can be all irregular because of the grooves.

I am sure that it doesn't have a regular bounce anyway, yeah this bounces all irregular.

A good looking ball, short felt, narrow lines so the bounce was true.

There were no imperfections in (the bounce) it never deviated.

Yeah when you put top spin on your serve it was really kicking up it was really exaggerating the spin.

It is a top spin ball, because it was really kicking up on the bounce.

On a slice serve or slice shot this ball stays a lot lower than the last one.

I would say that this is a slice ball. It hugs the floor a bit more on the slice.

I mean all the balls were reasonably high bouncing but you would expect that with any decent tennis ball on a court like this.

---

Base Themes

- Light on bounce
- Heavy on bounce

High Order Sub-Themes

- Weight of bounce
- Effect of bounce on shot selection
- Predictable bounce
- Irregular bounce
- Characteristics of bounce
- True bounce
- Top spin acts on bounce
- Slice acts on bounce
- Effect of spin on bounce
- Effect of the court on the bounce

General Dimension

Figure 3.4b: General Dimension - Bounce (2)
Example Quotes

This ball is very responsive to spin

The ball hit the racket and you could put the spin you wanted on to the ball, you had enough time, say if you wanted to change the spin

It feels as though you can put more spin on it because it's a bit slower, it stays on the racket for a bit longer so you can put a bit more spin on it and really perhaps work the ball

They take spin very well, or they take spin too much really

You needed to work quite hard to get topspin on it

They were less responsive to spin than the last balls. It was a real effort to get any work on the ball.

It's a good ball, it slightly deformed when it hit the strings so you've got that extra second or so to control it

You felt as though you could feel the ball on the racket enough time to control it

It seemed to be the easiest ball to get in. The ball had grip and feel on the strings. It seemed to grip the strings nicely. The nap and the felt gripped onto the strings and felt nice as you hit it.

Because it's a bit harder you couldn't control the ball as much because it's coming straight back off the strings quicker rather than deforming on the strings and you've got that split second to control it

It's a ball that doesn't have a lot of friction on your strings it sort of comes off them quite fast

It's coming off the racket quite fast, it's quite pingy and flying all over the place. I would take a couple of games to get used to that

Figure 3.5: General Dimension - Control
### Example Quotes

- It's big, a lot bigger than the other ones
- That's a big ball, a big ball
- Slightly oversized
- I think this ball is smaller than the others. To be honest I think the Wilson is smaller than the Dunlops, Slazengers and most balls to be honest.
- Smaller, I think it is smaller than the other one was
- It's smaller, amazing, but it looks a bit smaller
- The size of them looks standard tennis ball size, I didn’t notice them being any smaller or bigger
- They are certainly easier to see, obviously, they are bigger
- And big in the air, you could really see it and see it right off his racket
- There are different colour grooves, these are yellow whereas the others are white. I think it doesn’t help the picking out as easily
- A good looking ball, short felt and narrow lines so the bounce was true
- A narrow seamed ball
- Yeah because the way it folds in and out is more pronounced, it was a smoother, it’s less spherical I think than the last ball.
- The felt is denser, more densely packed together so it’s frayed less than the last ball.
- Thick, high density felt
- The quality of the felt is better than the first one. It’s the best quality felt I’ve used and it’s more compacted so I think it would wear better than the first ball.
- High quality felt but loosely packed just looks like it’s going to wear out quick

### Base Themes

- Bigger than normal
- Smaller than normal
- Normal sized
- Increased visibility due to size

### High Order Sub-Themes

- Size of ball ridges
- Sphericity of ball
- Density of felt
- Ball cloth
- Effect of colour of grooves on visibility

### General Dimension

- Appearance

---

**Figure 3.6: General Dimension - Appearance**
Example Quotes

The pressure just doesn't go no matter how worn they are on the outside it's a good ball on the inside still.

This ball would keep its pressure for a long time.

I can imagine those balls after a while going a bit flat.

These balls as they wear will tend to get a bit flat.

They did feel that if you played a match with them, then they would fluff up quite a bit.

It's quite fluffy round the sides.

This ball has fluffed up quite badly so it's a lot bigger and slower now.

This ball will lose all it's fluff and become what we call a skinhead.

These are becoming thinner on top and are not fluffing up at all.

It's going to wear out especially on clay or astro they are going to be eaten up by the courts a lot more.

No if anything on these courts with these type of balls it will eat away at the surface of the ball so it will wear down and probably go even quicker I would have thought.

You'll be able to keep playing and playing with them, they are really durable.

I've coached in a club that used these balls, very popular for the members because a can will last them. Joe Punter on an Astroturf court could use a can of these for half a summer and they will be the same ball it will stay, because of the thickness it will stay, its character will remain and because of the density of the felt and the poor condition of the felt it will just stay on.

Good for durability, good for mum in a ladies 4 for durability.

Also a lot more wear on the ball, fluff is coming off so they are not going to last so long.

These balls are going really quickly. After a set with these balls they would be ripped to pieces.

Figure 3.7: General Dimension - Ball Wear
Example Quotes

These balls were really quick through the air
They were the quickest balls through the air that we have used
They were pretty quick weren't they
Definitely slower through the air
It was noticeably slower through the air
They don't fly very fast

These were in the middle of all the balls we have used. Just an averaged pace ball.

On the serve because it's heavier I think and because naturally we sort of hit down on our serves so naturally because it's heavier and more gravity I was really struggling to get it over the net. I would have had to make a conscious change to hitting up more on my serve than normal as literally just the mass of it was bringing it down.

This ball is almost like changing surfaces, you have to alter your trajectory, you've got to hit it higher

It's a lighter ball so it tends to float, I mean it's not that big amount but you can see it sometimes

Very light, well again it's difficult to explain I think. It's very light through the air

These balls were light which meant that they were swerving in the air a little bit

This is a much heavier ball through the air, which means that it's flight stays true

That ball didn't fly as much, so it was easier to get in. I don't think we hit a ball long for the duration of the warm-up

This ball is basically just easier to get in the court

This ball feels quite hard to over hit because you have to hit it hard to hit it out

The problem with a light ball is because they seem to fly very well it's very easy to hit the ball out or over hit the ball.

One thing I did notice was they are very responsive they really flew when you hit the shot. You expected it to dip in but actually it seemed to carry in the air.

It did feel lighter so sometimes if you sort of didn't concentrate too much on one shot and hit it, it sort of flew through the air a bit. You had to remember that you need to put spin on it to get it in.

The topspin serves that I hit they just didn't move, I found with the Slazenger I could get the ball to move in the air quite a lot whereas these ones seem to not give me much

I found it a bit more difficult from the serve putting the slice and kick on it where it's bigger it's not cutting through the air it's sort of riding the air and not swinging out as much

Because it's softer it's not flying through the air as quickly and because it's softer you can work the spin a bit more so therefore the flight of the ball comes a little bit slower because the ball's not traveling through the air straight it's obviously turning so you've more chance to see the ball and get yourself in the right position to hit it

---

Base Themes

Quick through air
Slow through air
Average pace through air

High Order Sub-Themes

Speed of flight
Adjustment to flight trajectory
Weight through air
Ability to control flight

General Dimension

Ball Flight

Figure 3.8: General Dimension - Ball Flight
### Example Quotes

*I liked using those balls*

Yeh, I liked using those balls, they had quite a nice feel.

They weren't as bad as what I remember Tretoms to be.

It was my idea of what a good quality tournament ball should be like.

Good ball, good ball. What I would consider to be a high quality tournament ball.

I liked using those balls actually. They are a bit slower so that suits my style of game. It might give me a chance.

They feel really comfortable to play with, I wouldn't have any concerns playing with these balls at all.

Much more comfortable to hit with from the start.

I'd have concerns about injury using that ball.

They are horrible, tennis elbow written all over them.

It felt horrible, it seemed like a cheaper ball, a real tinny feel, you could hear it as well from the sound.

Whether it's more of a tournament ball I don't know, I would have thought there would be issues from my perception of it about the quality of the ball. I would be surprised, although it says US Open on it to find that this is used at the US Open, this exact ball but I might be wrong.

Absolutely hideous, horrendous, that is the worst ball I have ever used.

I hate those balls!

Yeah, OK it was a really unpleasant feel with that ball.

I didn't like using that ball. It had a really unpleasant feel when you hit it.

To get any pace into the ball, you really have to hit the ball, so it was slightly more tiring to play with, it took more effort to get the same pace in the ball.

That ball is really hard work. It is a real effort to play with.

I get found out with a ball like this, high kicking topspin hides my more traditional strokes, so yeah, this would be more of a baseliners ball.

I play a faster serve and volley game, so this ball is definitely not suited to me.

I don't really see the point of this [bigger] ball, it would slow down grass tennis significantly, it would certainly make grass tennis more like the '70s. You'd have to be, I mean the ball is called a Precision, it's all about you having to be able to be precise pushing it around without much spin.

Oh well, we will last about five seconds on this one. I just hate Tretorn balls.

I mean, I know what I am going to say about this one because I have previous experience of knowing about these balls.

---

### Base Themes

- Like using
- Better than expected
- Good quality of ball
- Suits style of play
- Comfortable to play with
- Concerns over injury
- Cheap quality of ball
- Dislike using
- Unpleasant feel
- Effort to play with
- Not suited to style of play
- Size

### High Order Sub-Themes

- Positive responses
- Negative responses

---

### General Dimension

**Players' Psychology**

---

![Figure 3.9: General Dimension - Players' Psychology](image-url)
a): How hard would the ball feel?  
Mean-3.8, Standard deviation 0.63

b): How heavy would the ball feel?  
Mean-3.2, Standard deviation 0.80

c): How quick would the ball be off the racket?  
Mean-3.9, Standard deviation 0.86

d): How would the ball sound?  
Mean-3.2, Standard deviation 0.93

e): How loud would the ball sound be?  
Mean-3.2, Standard deviation 0.82

f): How long would the ball sound last?  
Mean 2.6, Standard deviation 0.90

Figure 3.11a-f: Questionnaire responses for ideal ‘feel’ of a tennis ball
g) **How much vibration would you feel?**

Mean: 2.1, Standard deviation: 0.90

---

Figure 3.11g: Questionnaire responses for ideal ‘feel’ of a tennis ball
Figure 4.1: Normal equal-loudness-level contours for pure tones (ISO 226:2003)
Figure 4.2 – Effect of duration on the threshold of pure tones (Yost, 1994)

Figure 4.3 – Effect of masking bandwidth on signal threshold. Identifies the critical bandwidth at which further increases in bandwidth do not change the signal threshold significantly (Moore, 2003)
Figure 4.4: Width of the critical bands as a function of centre frequency (Levine, 2000)

Figure 4.5: Relationship between perceived loudness in sones and the intensity level of a sound (Levine, 2000)
Figure 4.6: Commonly used sound weighting networks

Figure 4.7: Sound pressure discrimination measured in terms of the Weber fraction for various SPLs and frequencies of sound (Coren et al., 1999)
Figure 4.8 – Effect of bandwidth on loudness. As the bandwidth increases beyond the critical bandwidth (250-300Hz) the loudness of the complex sound increases (Moore, 2003)

Figure 4.9 – Difference threshold for frequency as a function of frequency (Yost, 1994)
Figure 4.10: Weber fraction for frequency discrimination (Yost, 1994)

Figure 4.11. Cross-section of skin showing the dermis and epidermis (Griffin, 1990)
Figure 4.12 – Threshold of perception curves for various studies (Roberts, 2002)

Figure 4.13 – Measurement locations for transmissibility tests (Reynolds & Angevine, 1977)
Figure 4.14 – Average values transmissibility curves for vibration in the (a) vertical (b) horizontal and (c) axial directions for a 9N finger grip. Curves 1-8 represent measurement locations in Figure 4.13 (Reynolds & Angevine, 1977)
Figure 4.15 - Calculated ratios of the vibration levels at the elbow divided by the vibration levels at the wrist for vibration in the horizontal and vertical directions (Reynolds & Angevine, 1977)
Figure 4.16 – Bones of the right hand and arm (Tortora, 1995)
Figure 4.17 – Anatomical and basicentric coordinate systems for hand transmitted vibration (ISO5349:1, 2001)

Figure 4.18 – Frequency weighting curve for hand-transmitted vibration (ISO:5349:1, 2001)
Figure 5.1 - Cumulative probability vs. Score/n

Figure 5.2: Racket mounted accelerometer
Figure 5.3 – Vibration grip adaptor

Figure 5.4 – Accelerometer skin mounting configuration
Figure 5.5 – Mounting frequency response
Figure 6.1: Subjective analysis methodology
Figure 6.2a-h: Bradley Terry model fit for sound experiment
Balls separated by a red dashed line may be considered significantly different

Figure 6.3: Results of t-test for sound data
(d) Q4: Ball Vibration

Less Vibration: -0.8, -0.6, -0.4, -0.2
More Vibration: 0.2, 0.4, 0.6, 0.8

With sound:

Without sound:

Less Vibration: -0.8, -0.6, -0.4, -0.2
More Vibration: 0.2, 0.4, 0.6, 0.8

Combined:

Less Vibration: -0.8, -0.6, -0.4, -0.2
More Vibration: 0.2, 0.4, 0.6, 0.8

(e) Q5: Ball Speed

Faster: -0.8, -0.6, -0.4, -0.2
Slower: 0.2, 0.4, 0.6, 0.8

With sound:

Without sound:

Faster: -0.8, -0.6, -0.4, -0.2
Slower: 0.2, 0.4, 0.6, 0.8

Combined:

Slazenger: ●
Tretorn: ♦
Absorber: ○
Precision: ▲

Figure 6.4a-e: Bradley Terry model fit for vibration experiment
Figure 7.1a- A-weighted all balls sound spectra for 0-10kHz

Figure 7.1b- A-weighted all balls sound spectra for 0-3kHz
Figure 7.2: Sample sound data capture (A-weighted)

Figure 7.3: Sound decay curve (A-weighted)
Figure 7.4: Peak-to-peak values for all balls used for each player. Error bars represent one standard deviation.

Figure 7.5a: A-weighted averaged sound spectra for all balls for a single player for a frequency range of 0-10kHz.
Figure 7.5b: A-weighted averaged sound spectra for all balls for a single player for a frequency range of 0-3kHz.

Figure 7.5c: Spectrum from racket mounted accelerometer
Figure 7.6a-b: Sample vibration measurements for measurement locations X1 and X2 (grip)

Figure 7.6c-d: Sample vibration measurements for measurement locations X3 and X4 (knuckle & wrist)

Figure 7.6e: Sample vibration measurements for measurement locations X5 (elbow)
Figure 7.7: DRMS grip values for all balls used for each player. Error bars represent one standard deviation.

Figure 7.8a: Frequency spectrum for measurement location X1 (grip) for one player for all balls.
Figure 7.8b: Frequency spectrum for measurement location X2 (grip) for one player for all balls

Figure 7.8c: Frequency spectrum for measurement location X3 (knuckle) for one player for all balls
Figure 7.8d: Frequency spectrum for measurement location X4 (wrist) for one player for all balls

Figure 7.8e: Frequency spectrum for measurement location X5 (elbow) for one player for all balls
Figure 9.1: HSV of Slazenger ball at 40m/s showing deformation of front and back of ball

Figure 9.2: 3DOF tennis ball model
Appendices
Appendix A

Ball Testing Guidelines
(International Tennis Federation, 2004)

ITF Tennis Ball Regulations

a. The ball shall have a uniform outer surface consisting of a fabric cover and shall be white or yellow in colour. If there are any seams they shall be stitchless.

b. The ball shall conform to these requirements and have a weight (mass) of more than 1.975 ounces (56.0 grams) and less than 2.095 ounces (59.4 grams).

c. More than one type of ball is specified. Each ball shall have a bound of more than 53 inches (134.62 cm) and less than 58 inches (147.32 cm) when dropped 100 inches (254.00 cm) upon a flat, rigid surface e.g. concrete. Ball Type 1 (fast speed) shall have a forward deformation of more than .195 inches (.495 cm) and less than .235 inches (.597 cm) and return deformation of more than .265 inches (.673 cm) and less than .360 inches (.914 cm) at 18 lb (8.165 kg) load. Ball Types 2 (medium speed) and 3 (slow speed) shall have a forward deformation of more than .220 inches (.559 cm) and less than .290 inches (.737 cm) and return deformation of more than .315 inches (.800 cm) and less than .425 inches (1.080 cm) at 18 lb (8.165 kg) load. The two deformation figures shall be the averages of three individual readings along three axes of the ball and no two individual readings shall differ by more than .030 inches (.076 cm) in each case.

d. For play above 4,000 feet (1219 m) in altitude above sea level, two additional types of ball may be used.

i. The first type is identical to Ball Type 2 (medium speed) as defined above except that the ball shall have a bound of more than 48 inches (121.92 cm) and less than 53 inches (134.62 cm) and shall have an internal pressure that is greater than the external pressure. This type of tennis ball is commonly known as a pressurised ball.
ii. The second type is identical to Ball Type 2 (medium speed) as defined above except that the ball shall have an internal pressure that is approximately equal to the external pressure and have been acclimatised for 60 days or more at the altitude of the specific tournament. This type of tennis ball is commonly known as a zero-pressure or non-pressure ball.

The third type of ball which is recommended for use for play on any court surface type above 4,000 feet (1219 m) in altitude is the Ball Type 3 (slow speed), as defined above.

e. All tests for bound, size and deformation shall be made in accordance with the regulations below.

**ITF Regulations for making tests**

i. Unless otherwise specified all tests shall be made at a temperature of approximately 68° Fahrenheit (20° Celsius) and a relative humidity of approximately 60%. All balls shall be removed from their container and kept at the recognised temperature and humidity for 24 hours prior to testing, and shall be at that temperature and humidity when the test is commenced.

ii. Unless otherwise specified the limits are for a test conducted in an atmospheric pressure resulting in a barometric reading of approximately 30 inches (76 cm).

iii. Other standards may be fixed for localities where the average temperature, humidity or average barometric pressure at which the game is being played differ materially from 68° Fahrenheit (20° Celsius), 60% and 30 inches (76 cm) respectively. Applications for such adjusted standards may be made by any National Association to the International Tennis Federation and, if approved, shall be adopted for such localities.

iv. In all tests for diameter, a ring gauge shall be used consisting of a metal plate, preferably non-corrosive, of a uniform thickness of one-eighth of an inch (.318 cm). In the case of Ball Type 1 (fast speed) and Ball Type 2 (medium speed) balls there shall
be two circular openings in the plate measuring 2.575 inches (6.541 cm) and 2.700 inches (6.858 cm) in diameter respectively. In the case of Ball Type 3 (slow speed) balls there shall be two circular openings in the plate measuring 2.750 inches (6.985 cm) and 2.875 inches (7.302 cm) in diameter respectively. The inner surface of the gauge shall have a convex profile with a radius of one-sixteenth of an inch (.159 cm). The ball shall not drop through the smaller opening by its own weight and shall drop through the larger opening by its own weight.

v. In all tests for deformation conducted under Rule 3, the machine designed by Percy Herbert Stevens and patented in Great Britain under Patent No. 230250, together with the subsequent additions and improvements thereto, including the modifications required to take return deformations, shall be employed. Other machines may be specified which give equivalent readings to the Stevens machine and these may be used for testing ball deformation where such machines have been given approval by the International Tennis Federation.

vi. The procedure for carrying out tests is as follows and should take place in the order specified:

a. Pre-compression – before any ball is tested it shall be steadily compressed by approximately one inch (2.54 cm) on each of three diameters at right angles to one another in succession; this process to be carried out three times (nine compressions in all). All tests are to be completed within two hours of pre-compression.

b. Weight (mass) test (as above).

c. Size test (as in paragraph iv above).

e. Deformation test – the ball is placed in position on the modified Stevens machine so that neither platen of the machine is in contact with the cover seam. The contact weight is applied, the pointer and the mark brought level, and the dials set to zero. The test weight is placed on the beam in a position that is equivalent to a load of 18 lb (8.165 kg) on the ball, after which the wheel is turned at a uniform speed such that five seconds elapse from the instant the beam leaves its seat until the pointer is brought
level with the mark. When turning ceases the reading is recorded (forward deformation). The wheel is turned again until figure ten is reached on the scale (1 inch (2.54 cm) deformation). The wheel is then rotated in the opposite direction at a uniform speed (thus releasing pressure) until the beam pointer again coincides with the mark. After waiting ten seconds, the pointer is adjusted to the mark if necessary. The reading is then recorded (return deformation). This procedure is repeated on each ball across the two diameters at right angles to the initial position and to each other.

e. Bound test (as above) – measurements are to be taken from the concrete base to the bottom of the ball.
Appendix B

Online questionnaire for evaluation of ball ‘feel’

DETERMINING FEEL IN TENNIS BALLS

Loughborough University Sports Technology Research Group are conducting research into the 'feel' of sports equipment. For this particular study, tennis balls are the focus of investigation. Following from previous research, a number of factors were identified. This questionnaire aims to distinguish the relative importance of each.

The questionnaire is anonymous and your participation is most appreciated. The results will be used for continuing PhD research. For any additional questions please contact g.t.davies@lboro.ac.uk, or visit the Loughborough Sports Technology website by clicking HERE.

______________________________

BACKGROUNDF QUESTIONS

<table>
<thead>
<tr>
<th>Age</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>What age did you start playing tennis?</td>
<td></td>
</tr>
<tr>
<td>Rating (or standard if not known)</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>Male</td>
</tr>
<tr>
<td>Are you a coach, and if so what level?</td>
<td>Yes</td>
</tr>
<tr>
<td>Level</td>
<td></td>
</tr>
<tr>
<td>Where did you hear about the questionnaire?</td>
<td></td>
</tr>
</tbody>
</table>

______________________________

DURING AN IDEAL GAME

<table>
<thead>
<tr>
<th>1a How hard would the ball feel?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1b How important is the soft/hard feel?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2a What would the weight of the ball be?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Question</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------------------------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2b</td>
<td>How important is the weight of the ball?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>How quickly would you feel the ball to have left the racket face?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>How important is the speed of the ball off the racket face?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>How would the ball sound?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4b</td>
<td>How important is the pitch of the ball sound?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>How loud would the ball sound be?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5b</td>
<td>How important is the loudness of the ball sound?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6a</td>
<td>How long would the sound last?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6b</td>
<td>How important is the duration of the ball sound?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7a</td>
<td>How much vibration would you feel?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7b</td>
<td>How important is the level of vibration you feel?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>How important is the consistency of the bounce?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>How important is the controlability of the ball on the racket face?</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>---</td>
<td>---------------------------------------------------------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>How important is the ability to apply spin to the ball?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>How important is the wear of the ball?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>How important is the general appearance of the ball?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>How important is the size of the ball?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>How important is the ability to control the ball’s flight?</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Important</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Submit