Tennis ball degradation

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TENNIS BALL DEGRADATION

by

Carolyn Steele

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

Doctor of Philosophy

Loughborough University

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Abstract

Despite anecdotal evidence of changes to tennis ball characteristics and play properties, little research has been directed towards understanding the causes and effects of tennis ball degradation. Improved racket technology and player fitness have contributed to an increase in the speed of the game, yet balls have seen few advancements over the same period. There are several obvious factors contributing to tennis ball degradation: natural pressure loss in pressurised balls, changes to the cloth covering due to court and racket impacts, and precipitation and environmental factors. As recent tennis research has focused on the properties of new balls, there is a need to investigate other ball conditions present in the game of tennis.

This thesis provides a structured investigation into the causes and effects of ball degradation, an objective assessment of the effects of degradation on ball performance, and incorporates subjective perceptions of ball aesthetics and play properties noted by players. Particular attention is given to ball fuzziness. Excessive fuzziness can occur from manufacturing variability, court and racket interactions, and environmental conditions - though there is currently no standardised method to assess ball surface condition.

An objective measure of ball fuzziness has been developed and used in the analysis of nearly 4000 individual ball images. The effects of court and racket impacts, precipitation, natural pressure loss, and repeated impacts have been analysed for their effects on ball degradation. An assessment of ball performance utilised ball impact and aerodynamic data to determine significant differences between balls and develop an improved ball trajectory model.

Several player perception investigations were conducted using professional, elite, and standard club players. Two internet based investigations incorporated aspects of sensory evaluation studies to produce new techniques in evaluating products for the sports industry. An investigation into ball aesthetics was used to determine the relative importance of ball attributes on ball playability and important areas of perceived ball feel and performance were assessed during testing with elite players. Significant differences in perception were then combined with objective data to establish perceptible thresholds of wear and degradation in tennis balls and significant areas in player perception.

This thesis presents a large body of work on tennis ball degradation. Results provide a mechanism to structure future investigations, new analysis techniques, and objective and subjective analyses of ball degradation. The developed digital fuzziness metric shows good agreement with player perception and aerodynamic data and provides a method to objectively compare ball conditions. Naturally aged and fuzzy balls produced the most noticeable differences in ball impact properties, though the aerodynamic data used in the development of an improved trajectory model suggests that ball spin could play a more significant role in ball flight than drag force differences.

Subjective assessments of ball appearance suggest ball fuzziness is nearly twice as important as the condition of the ball’s logo in determining ball playability. Player testing indicated inconsistent responses and limited differentiation in the perceived feel and performance properties of naturally aged balls. The visible differences in the fuzzy balls improved player responses, indicating the importance of aesthetics in perceived ball properties. Flight speed, hardness, liveliness, bounce speed, and bounce height are areas of perceived ball feel and performance that show good agreement with measured ball properties and usefulness in future work.

Directions for future work include developing a ball performance model, expanding the digital fuzziness metric to produce an overall measure of ball degradation, and further laboratory and perception testing.
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I would also like to thank my family and friends for their continued encouragement and support through all of my adventures on the road less travelled.
Publications arising from this work


“Real knowledge is to know the extent of one's ignorance.”

- Confucius
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Nomenclature

\(\alpha\)  Significance level
\(\alpha_c\)  Cronbach's alpha
\(\bar{r}\)  Average inter-correlation between items
\(\bar{x}_i\)  Sample mean
\(\bar{R}_j\)  Average rank for each sample
\(\bar{R}\)  Average of all sample ranks
\(\bar{z}\)  Sample mean
\(\beta_i\)  Attribute utilities
\(\chi^2\)  Distribution similar to normal distribution
\(\ddot{x}\)  Acceleration (ms\(^{-2}\))
\(\Delta t\)  Time increment (s)
\(\dot{x}\)  Velocity (ms\(^{-1}\))
\(\lambda\)  Number of times an object pairing is evaluated
\(\mu\)  Fluid viscosity (kgm\(^{-1}\)s\(^{-1}\))
\(\mu_f\)  Coefficient of sliding friction
\(\nu\)  Scale value determined from Bradley-Terry model
\(\omega\)  Spin rate (rpm)
\(\omega_{in}\)  Inbound spin (rpm)
\(\omega_{out}\)  Outbound spin (rpm)
\(\rho\)  Fluid density (kgm\(^{-3}\))
\(\sigma\)  Standard deviation
\(\sigma_X\)  Experimental standard deviation
\(\nu\)  Fluid velocity (ms\(^{-1}\))
\(\zeta\)  Kendall's coefficient of consistence
\(A\)  Frontal area (m\(^2\))
\(a(s_t)\)  Average dissimilarity to assigned cluster
\(A_{1}\)  Accelerometer location 1
\(A_{2}\)  Accelerometer location 2
\(a_{ij}\)  Paired comparison responses
\(b(s_t)\)  Average dissimilarity to second best cluster
\(b(x,y)\)  Thresholded image
\(c\)  Damping (Nsm\(^{-1}\))
\(C_D\)  Drag coefficient
\(C_L\)  Lift coefficient
\(a_t\)  Number of circular triads
\(D\)  Diameter (m)
\(d_i\)  Difference in rank between an object pair
\(E\)  Error
\(e_x\)  Coefficient of restitution in the tangential direction
\(e_y\)  Coefficient of restitution in the normal direction
\(F\)  Force (N)
\(f(x,y)\)  Greyscale image
\(F_D\)  Drag force
\(F_r\)  Fisher's variance ratio distribution
\(k\)  Block size
\(k_c\)  Number of clusters
\(k_s\)  Stiffness (Nm\(^{-1}\))
\(L\)  Length of roughness profile
\(m\)  Mass (kg)
\(N\)  Number of panellists
\(n\)  Sample size
\( N_p \) Number of object pairs
\( p \) Probability
\( R \) Radius (m)
\( r \) Pearson correlation coefficient
\( R^2 \) Goodness of fit
\( R_A \) Arithmetical mean deviation of a roughness profile (mm)
\( r_s \) Spearman rank order correlation
\( R_Z \) Mean roughness depth (mm)
\( Re \) Reynold's number
\( S \) Spin ratio of rotational and linear velocities
\( s \) Average silhouette statistic for clustering process
\( s_i \) Clustered data point
\( \text{sil}(s_i) \) Silhouette statistic for a single data point
\( SS \) Sum of squared deviations from the mean
\( T \) Friedman statistic
\( t \) Number of objects
\( T_c \) Contact time (s)
\( t_{a/2, DOF} \) \( \alpha/2 \) critical value from the t-distribution
\( Th \) Threshold level
\( u \) Kendall's coefficient of agreement for paired comparisons
\( v \) Rank value
\( V_{fa} \) Outbound horizontal velocity (ms\(^{-1}\))
\( V_{in} \) Inbound velocity (ms\(^{-1}\))
\( V_{ix} \) Inbound horizontal velocity (ms\(^{-1}\))
\( V_{iv} \) Inbound vertical velocity (ms\(^{-1}\))
\( V_{out} \) Outbound velocity (ms\(^{-1}\))
\( W \) Coefficient of concordance
\( X \) Mean value
\( x \) Displacement (m)
\( x_0 \) Initial displacement (m)
\( x_i \) Data value
\( y \) Rating value
\( y(x) \) Roughness profile
\( z_i \) Dummy variable for regression analysis
\( \text{CCD} \) Charge coupled device
\( \text{CM} \) Centre of mass
\( \text{COR} \) Coefficient of restitution
\( \text{DFM} \) Digital fuzziness metric
\( \text{DOF} \) Degrees of freedom
\( \text{GUI} \) Graphical user interface
\( \text{HSD} \) Tukey's Honestly Significant Difference
\( \text{ITF} \) International Tennis Federation
\( \text{LSD} \) Fisher's Least Significant Difference
\( \text{LS} \) Least squares
\( \text{MCC} \) Minimum circumscribed circle
\( \text{MIC} \) Maximum inscribed circle
\( \text{MZ} \) Minimum zone circle
\( \text{OLS} \) Ordinary least squares
\( \text{PL} \) Pressureless core
Chapter 1

Introduction

In the last century, tennis has evolved from a social game of the elite to a modern game enjoyed by millions around the world. Throughout this development, improvements in player fitness and racket technology have increased the speed of the game dramatically. The tennis ball, however, has seen limited advances during this period yet it must withstand increased impact forces during play. Professionals use balls for as little as nine games, while recreational and club players may use balls over the course of several sets, matches, weeks, or even months due to the cost of replacement. Despite anecdotal evidence of changes to ball characteristics and play properties, little research has been directed towards understanding the causes and effects of ball degradation. This thesis investigates factors causing ball degradation, changes in ball performance, and resulting effects on player perception. With the development of these relationships, manufacturers will be able to optimise important factors in degradation, minimise their effects of player perception, and improve opinions towards overall ball quality and brand reputation.

1.1 History and Development of Tennis

The origins of tennis have been associated with a ball and paddle sport played by the Greeks and Romans, though more accepted roots concerning today's game rise from a hand ball game played by French monks in the 11th and 12th centuries. Referred to as 'jeu de paumme' or 'game of the hand,' it was enjoyed so much that the Pope tried to ban the playing of it. As the game gained popularity it continued its evolution towards modern day tennis; indoor courts replaced courtyards, and gloves, paddles, and eventually webbed paddles were used in place of the hand. By the 1500's, a wooden racket was in use with a cork-cored ball. Tennis gained esteem in the 1830's with more elastic balls made from newly discovered vulcanised rubber on outdoor grass courts. Equipment and rules similar to those in modern tennis were first patented in 1874 and the game's growth continued with the start of the Wimbledon Championships three years later (Clerici, 1976).

With over 60 million participants worldwide, and 191 affiliated nations, tennis is truly a global sport (ITF, 2006b). This popularity, however, has resulted in a range of players and consumers with varying demands. Professional players demand 'top-of-the-line' rackets and balls as they are more sensitive to equipment parameters and are not limited by cost. Recreational players, who play less frequently, must look for a balance between cost and performance. In Great Britain, there are over 3.5 million players, with more than 1.16 million playing more than 25 times a year. The British Tennis Market Report found that balls were the most frequently purchased item, with nearly half of consumers purchasing balls and a strong correlation between ball purchases and the average days played in a year (LTA, 2004). While the average amount spent on balls was £23, this figure was higher among older players aged 35-44 (£41), club social (£35), and club team (£38) players.
1.2 The Tennis Ball Problem

During play, tennis balls have the ability to be played out of compliance with standardised ball specifications as the internal pressure, rubber, and cloth undergo the rigours of play. Despite increasing attention devoted to racket technology and the rising forces and speeds associated with modern tennis, relatively few resources have been directed towards furthering ball construction and development. Balls that were once capable of lasting several sets, now face durability issues and must be changed more frequently to remain acceptable.

In 1924, the International Lawn Tennis Federation became the official global organisation to establish and control the rules of tennis. In 1948, an International Ball Committee was set up to investigate the standardisation of tennis balls around the world, with the hope of developing a tool to test balls at game speeds (ITF, 2006b). Current balls approved for play by the International Tennis Federation (ITF) must meet size and mass restrictions, forward and return compression measurements, and rebound requirements from a 254cm drop test (ITF, 2006c).

There are several obvious factors contributing to changes in ball properties: natural pressure loss in pressurised balls, changes to the cloth covering through court and racket impacts, and precipitation and environmental factors. Little structured work has been done to address potential effects of these factors in ball performance and player perception. Rand et al. (1979) used static testing to observe effects of repeated impacts and pressure loss on pressurised balls, but performed no dynamic testing. Haake et al. (2003) simulated pressure loss using a punctured ball in dynamic testing while Miller & Messner (2003) used a wear rig to repeatedly impact balls and monitor changes to the coefficient of restitution. Work has also been done to investigate friction, temperature, and aerodynamics of tennis balls (Bao et al., 2003; Chadwick & Haake, 2000b; Mehta & Pallis, 2001a; Rose et al., 2000). In most cases, however, ball degradation has not been the primary focus of the research and used only to add an additional dimension to work focusing on characterising new tennis balls. At present the determination of when a ball is unfit for play is subjective, though some manufacturers have attempted to standardise visual assessments of ball condition. Abnormal ball degradation and unacceptable balls result in quality returns at a cost to manufacturers and a loss of brand reputation.

In addition to examining performance properties with a systematic and structured approach, there is also a need to relate player perception of feel and performance to collected data. Davies (2005) investigated the feel of tennis balls during impact while Roberts (2002) develops a similar methodology for golf shots. Haake & Goodwill (2002) characterise feel in tennis impacts using the coefficient of restitution and dynamic ball stiffness. In this thesis, degradation refers to any changes to ball characteristics while wear is limited to those caused from play. Ball fuzziness refers to the surface condition of a tennis ball.

1.3 Aims and Objectives

While there has been much recent research into both dynamic properties of tennis balls and the determination of factors important in ball performance, there has been limited investigation into balls during and after sustained use. Grand Slam Tournaments specify that balls should be changed after the first seven games, and then every nine games afterwards, to ensure that balls remain suitable for play (Grand Slam Committee, 2003). But for millions of club and recreational players, changes to balls over several sets, matches, weeks, and months are more relevant. There is a lack of understanding concerning changes throughout extended play and the point at which ball performance becomes unacceptable or potentially harmful to players. The relative importance of degradation factors is not known, nor their effects on play. Research into these areas will help manufacturers improve ball designs, provide information to governing bodies concerning acceptable levels of ball degradation, and allow players to make informed choices concerning ball use.

This thesis provides a structured investigation into the causes and effects of ball degradation, an objective assessment of the effects of degradation on ball performance, and incorporates subjective perceptions of ball aesthetics and play properties noted by players. In addition to this structured approach, there is
also an opportunity to relate player perceptions of ball properties to performance data - an area largely ignored in the current literature. Particular attention is given to ball fuzziness as some players consider a limited degree of fuzz desirable, as it improves control and allows more time to complete strokes, whereas others find it hinders ball speed and their ability to win points. Excessive fuzziness can occur from manufacturing process variability, court and racket interactions, and environmental conditions - though there is currently no standardised method to assess ball surface condition. Three major aims are addressed in this thesis:

1. Provide a mechanism for the structured investigation into the causes and effects of tennis ball degradation.
2. Provide an appropriate objective assessment of tennis ball degradation.
3. Provide an appropriate subjective assessment of tennis ball degradation.

Corresponding to these aims, the objectives of the research are to:

- Identify and investigate factors involved in causing ball degradation.
- Develop an objective, quantitative measure of ball fuzziness to correlate with player perception and aerodynamic data.
- Identify and investigate of changes in ball performance due to ball degradation.
- Identify and investigate of changes in player perception due to ball degradation.
- Relate objective ball measures to perceived ball feel and performance properties.

1.4 Thesis Structure

This thesis details work completed in the investigation of tennis ball degradation and the relationship between subsequent changes in ball performance and player perception of these characteristics. Chapter 2 reviews the current literature available concerning aspects of ball construction and design, ball degradation in tennis, ball performance measures, and player perception. The five problem objectives are developed in the following nine chapters.

Chapter 3 addresses the second objective regarding the development of a quantitative measure of ball fuzziness. Metric development and optimisation are discussed in detail, along with the implementation of a user interface for ball processing. Chapter 4 discusses the validation of this metric with ball performance and player perception data.

Chapter 5 investigates the causes of ball degradation, including play as well as other factors such as ball construction and natural pressure loss.

Aspects of ball performance have been separated into two main components: ball flight and impact. Chapter 6 details impact work for both court and racket impacts, while Chapter 7 presents a ball flight investigation using a wind tunnel capable of testing spinning ball samples at speeds up to 45 m s⁻¹.

Chapter 8 identifies important aesthetic ball attributes while Chapter 9 addresses player perception of tennis ball feel and performance. Chapter 10 discusses the relationship between measured changes in ball performance with player perception of ball condition.

Chapter 11 presents conclusions and directions for future research.
Chapter 2

Literature Review

This chapter contains an overview of relevant information concerning ball construction and performance, player perception, and ball degradation. Topics include manufacturing processes and playing standards, findings and measurement techniques relating to ball performance, components of player perception, and work already performed concerning ball degradation. Information and understanding in these areas will help structure future investigations into the causes of degradation and resulting effects on performance and player perception.

2.1 Ball Construction and Design

The rules of tennis state that the ball must be covered in a uniform fabric cover that is either white or yellow in colour, with any seams being stitchless. No requirements concerning ball core construction are specified, though the ball must conform to standard bounce, compression, size, and mass measures (ITF, 2006c). These rules have enabled the development of a range of internal cores and coverings used by manufacturers to achieve product objectives.

Balls generally may be classified into two types: pressurised and pressureless. Pressurised balls are usually considered to give players better playing performance and are used in the majority of elite tournaments. Pressureless balls are not affected by natural pressure loss and are more suited to recreational play over an extended period of time. Ball cores are currently composed of a mix of natural rubber and other ingredients to form a specific mixed compound capable of withstanding the stresses of the game. Typical core compound formulations for both pressurised and pressureless balls are shown in Table 2.1 (Blow, 1971).

A pressurised ball has a wall thickness of approximately 3mm, formed from a high-density, low-permeability compound to contain internal pressure. Gases and foams with larger molecular structures have also been used in place of air in attempts to lessen natural leakage through the rubber core. By

<table>
<thead>
<tr>
<th>Pressurised core</th>
<th>Pressureless core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Rubber</td>
<td>100</td>
</tr>
<tr>
<td>Clay</td>
<td>32</td>
</tr>
<tr>
<td>GPF Black</td>
<td>30</td>
</tr>
<tr>
<td>Zinc Oxide</td>
<td>9</td>
</tr>
<tr>
<td>Sulphur</td>
<td>3.5</td>
</tr>
<tr>
<td>DPG</td>
<td>2</td>
</tr>
<tr>
<td>HBS</td>
<td>1</td>
</tr>
<tr>
<td>Cure 2.5 min at 150°C</td>
<td>Cure 4 min at 150°C</td>
</tr>
</tbody>
</table>

Table 2.1: Ball core formulations, given in parts by mass (Blow, 1971).
comparison, a pressureless ball has a thicker wall with increased stiffness to produce similar size, mass, and bounce characteristics without the aid of increased internal air pressure for energy storage.

Elastomers, including natural and artificial rubber, have a low permeability to air and good adherence to various other materials - both of which are important in ball construction and performance. Rubber’s resilience and resistance to deformation is particularly important as deformation decreases with increasing compression loads, much like a steel spring (Nagdi, 1993).

There are two main types of cloth used in ball construction. Needle felt relies on mechanical fibre entanglement from fibres punched through a woven backing. Though it is appealing because of its cheap manufacture, needle felt is not known for its performance or wear tendencies. Woven felt is composed of a wool-nylon fibre mix and uses the scaled structure of the wool fibres, shown in Figure 2.1, to be mechanically felted and raised before being applied to the balls. A sateen weave is traditionally used in woven felt manufacture. It should be noted that this thesis focuses on the characteristics of sateen weave balls, except where specifically noted. Sateen weave balls are currently used in each of the Grand Slam Events and the majority of professional tournament play.

Figure 2.1: Wool fibre showing the scaled structure important in felting.

Structural characteristics of the cloth play an important role in ball performance as changes in yarn size, warp thickness, and dye can give the cloth a range of stiffness characteristics that combine with the ball’s core to determine overall ball play properties. A constant challenge in ball fabrication is optimising the cloth and rubber bond with changing cloth thickness, composition, and weight.

2.1.1 Standardised Testing

Size, mass, compression, and bounce height values specified by the ITF are shown in Table 2.2 (ITF, 2006c). In 2002, two new balls were approved for play: a larger ball (Type III) for use on faster surfaces and a harder ball (Type I) for use on slower surfaces. The standard ball is classified as a Type II ball. All ball types must have a mass between 56.0 and 59.4g and a rebound height between 134.62 and 147.32cm when dropped from a height of 254cm. Size measurements are determined using a series of machined rings which are used as a ‘go, no-go’ gauging system.

Compression is traditionally measured using a Stevens machine, shown in Figure 2.2(a), to apply a compression force of 80N to the ball, though this process has recently incorporated an automated compression machine. Forward compression is measured once the weight has been applied, and the return

| Table 2.2: Standardised testing ranges for approved ball types. |
|-----------------|-----------------|-----------------|
| Ball diameter(mm) | Forward compression(mm) | Return compression(mm) |
| Type I | 65.41 - 68.58 | 4.95 - 5.97 | 6.73 - 9.14 |
| Type II | 65.41 - 68.58 | 5.59 - 7.37 | 8.00 - 10.80 |
| Type III | 69.85 - 73.02 | 5.59 - 7.37 | 8.00 - 10.80 |

5
compression measured after the ball has been compressed by 2.54cm. Drop tests, as in Figure 2.2(b),
are usually performed with an automated release mechanism to eliminate human interaction during ball
release (Miller, 2004). Rebound heights can be determined using a video camera mounted to minimise
parallax errors.

2.2 Ball Performance

This section presents information on how balls differ in their physical performance, detailing both impact
and flight properties. Both rebound and contact measurements are discussed for court and racket impacts.
Flight differences, assessed using a variety of wind tunnel methodologies, are also summarised. While
only a limited amount of this performance related research has been used with worn balls, measurement
techniques and values for new balls will be useful in structuring future research.

2.2.1 Ball Impacts

A tennis ball’s bounce is determined by its elastic material properties and ability to store and convert
energy through the deformation of its shell and compression of internal pressure. While pressurised tennis
balls can use increased internal pressure as an effective means of energy storage, pressureless balls must
get their bounce entirely from the structure and elasticity of their rubber shell.

When a ball is dropped from a specific height, it will rebound to a lesser height due to energy losses
during impact. The ratio of these velocity values is used to assess this energy loss and is named the
coefficient of restitution (COR, $e_x$ in the horizontal and $e_y$ in the vertical directions). The coefficient of
restitution is easily observed through a ball’s normal impact with a rigid surface.

A ball rebounding to its drop height, or rebounding with the same exit velocity, is said to be perfectly
elastic ($e_y = 1$). This ideal ball loses no energy during impact. A ball that has no rebound from a
rigid surface is defined by $e_y = 0$. Cross (2000a) examined collisions between balls, determining that the
coefficient of restitution depends on the stiffness of each body involved in the impact, with rigid bodies
confining energy losses to the other body involved. During oblique impacts, $e_x$ is given by Equation 2.1
while $e_y$ is dependent only on component velocities (Cross, 2003a).

$$e_x = -\frac{V_{fz} - R\omega_{out}}{V_{iz} - R\omega_{in}}$$

Miller & Messner (2003) establish that the largest differences between pressurised and pressureless balls
occur at impact speeds less than 30 ms$^{-1}$, though higher testing speeds produced the largest differences
between balls sustaining repeated impacts. Ball COR is reduced after 50 to 100 impacts. Haake et al.

\[\text{Figure 2.2: Standardised testing techniques.}\]
(2003) find punctures decrease pressurised ball COR by 20% and stiffness by 35%. Pressurised balls also generally had higher COR and stiffness values than pressureless balls for normal impacts (Davies, 2005).

Static and low speed impacts produce minimal energy loss through material hysteresis (Ashcroft & Stronge, 2003). Increased energy losses during high speed impact testing can be attributed to the ball cloth that can elastically recover during static testing, but not during the brief impact of an actual bounce (Cross, 1999a). Cross (1999b) evaluates this property in tennis balls by comparing the area enclosed in both static and dynamic hysteresis curves. The dynamic curve is also characterised by a ‘kink’ from increased initial stiffness that does not appear during static testing.

Dynamic stiffness is influenced by the rubber core, internal air pressure, and deformation during impact, with lower energy losses in thinner rubber cores (Goodwill & Haake, 2000). The coefficient of restitution decreases non-linearly with increased impact speeds (Araki et al., 1996; Bridge, 1998; Miller & Messner, 2003). Increased impact speeds lead to increased contact areas and smaller contact times, while higher internal pressures contribute to smaller contact areas and contact times (Bridge, 1998).

**Racket Impacts**

Hatze (1993) determines that the majority of energy lost during a racket impact occurs in the racket recoil motion and internal racket vibrations, with only 20% of the initial kinetic energy in the system used to rebound the ball. For oblique racket impacts, ball COR ranges from 0.85 to 0.90, varying with ball inbound speed (Cross, 2003b). Hatze (1993) finds COR values of 0.755-0.848 for head clamped rackets. With unclamped rackets, the majority of energy loss occurs in frame recoil motion and internal vibration. Head clamping also eliminates differences in results due to grip tightness and energy dissipation.

Higher stringing tensions and racket stiffness produce larger and more varied COR values and smaller rebound angles (Bower & Sinclair, 1999). String type and tension, however, have negligible effects on ball spin (Brody et al., 2002; Goodwill & Haake, 2004b). Knudson (1991) finds more elastic combinations of string type and tension lead to more accurate ball rebound from the racket face when clamped at the handle.

The larger racket head sizes found in the modern game allow players to impact balls with larger racket angles and create more spin during impacts (Cross, 2005). Cottee (2002) finds differences in spin rates of up to 2000rpm with tangential velocities ranging from 15-30ms⁻¹. He finds rebound spin differences up to 500rpm between ball cores and traditional balls which supports the idea that surface condition and dynamic stiffness play an important role in the ball-racket interaction. Dynamic testing showed ball cores had noticeably higher COR values as compared to normal balls, suggesting the importance of ball cloth in energy losses.

Friction also plays an important role in the ball-racket interaction and the control many players feel they have over a shot. Cross (2000b) finds sliding friction values between 0.27 and 0.42 for new tennis balls with varied racket strings. While this study focuses on differences in string properties, it should be considered how the condition of the ball may affect these values and falsely be attributed to string differences. At low impact speeds there is a strong correlation between the static frictional force for a set of racket strings and ball speed and spin (Bao et al., 2002).

Ashcroft & Stronge (2002) examine the tangential force on balls due to surface friction and the mechanical interlocking of the ball felt and strings. During quasi-static testing, the coefficient of friction initially increases with increased normal force, but then proceeds to decrease. Limited normal forces during an impact cause the strings to embed in the ball’s felt cover and create higher frictional values, though higher forces reduce imbedding by compressing the felt and rubber.

**Court Impacts**

The International Tennis Federation (2006c) uses pace classification to categorise court surfaces and playing properties in the horizontal direction by calculating the coefficient of friction between a ball and a court surface during a low-angle oblique impact. The horizontal coefficient of restitution ($e_x$) is complicated by a
frictional force that affects the sliding to rolling transition during ball impacts (Brody, 1984). The vertical force on a ball can allow it to grip the surface with an increased static frictional force by stretching the ball horizontally (Cross, 2003b). A summary of \( e_x \) is presented in Table 2.3.

While the coefficient of restitution is derived from momentum and energy equations as a ratio of the velocity of separation to the velocity of approach, it ranges from +1 to −1 when used by several authors in oblique sports ball impacts (Meriam, 1975). These applications, though inconsistent with traditional mechanics, are modified to include both forward and reverse rebound directions. Cross (2002b) examines the horizontal coefficient of restitution for tennis balls on differing surfaces and found \( e_x \) to vary from -0.51 to 0.24 depending on the incident angle and coefficient of friction with the surface. Table 2.4 shows the relationship between incident ball angle, friction, and speed loss (Brody, 1997).

Spin is used in tennis as a way to increase control over ball placement. It can change the ball’s acceleration towards the court as well as influence ball rebound by creating increased or decreased horizontal velocity (Anderson & Anderson, 1982). A ball with topspin will accelerate downwards towards the court, causing it to bounce higher and lose less forward velocity from friction than a non-spinning ball. Table 2.5 relates pre and post bounce characteristics for different incoming spin rates. It is worth noting the differences in vertical velocity and post-bounce ball height due to initial spin.

| \( e_x \) = -1 | Frictionless surface. | \( V_{ix} = V_{fx}, \omega_{in} = \omega_{out} \) |
| -1 < \( e_x \) < 0 | Ball slides throughout bounce. | \( R_{\omega_{out}} < V_{fx} \) |
| \( e_x \) = 0 | Perfectly rough surface, velocity goes to zero. | \( R_{\omega_{out}} = V_{fx} \) |
| 0 < \( e_x \) < 1 | Ball grips ('bites') the surface. | \( R_{\omega_{out}} > V_{fx} \) |
| \( e_x \) = 1 | Kinetic energy conserved and elastic energy recovered. | |

### Table 2.4: Surface interaction summary (Brody, 1987).

<table>
<thead>
<tr>
<th>Incident angle of friction</th>
<th>Coefficient of friction</th>
<th>Corresponding court speed</th>
<th>Loss of forward ball velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Low</td>
<td>Fast</td>
<td>Small, proportional to friction</td>
</tr>
<tr>
<td>Small</td>
<td>High</td>
<td>Slow</td>
<td>Small, proportional to friction</td>
</tr>
<tr>
<td>Medium</td>
<td>Low</td>
<td>Fast</td>
<td>Medium</td>
</tr>
<tr>
<td>Medium</td>
<td>High</td>
<td>Slow</td>
<td>Large</td>
</tr>
<tr>
<td>Large</td>
<td>Low</td>
<td>Fast</td>
<td>Maximum</td>
</tr>
<tr>
<td>Large</td>
<td>High</td>
<td>Slow</td>
<td>Maximum</td>
</tr>
</tbody>
</table>

### Table 2.5: Pre and post bounce characteristics (Brody, 1987).

<table>
<thead>
<tr>
<th>Maximum height before bounce (cm)</th>
<th>Spin (rpm)</th>
<th>Vertical velocity on impact (m s(^{-1}))</th>
<th>Maximum height after bounce (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>147.3</td>
<td>1920 (back)</td>
<td>4.27</td>
<td>52.1</td>
</tr>
<tr>
<td>147.3</td>
<td>0</td>
<td>4.97</td>
<td>70.9</td>
</tr>
<tr>
<td>147.3</td>
<td>1920 (top)</td>
<td>5.52</td>
<td>87.4</td>
</tr>
</tbody>
</table>

The frictional force between the ball and court surface serves not only to slow the ball’s horizontal speed, but also to create a torque around the ball’s centre of mass. With small incident angles, a ball tends to slide throughout impact, as the normal force and resulting friction are not great enough to cause the ball to enter a rolling mode. Cross (2002b) determines that a high speed, low angle first serve should have a negative horizontal COR (\( e_x < 0 \)) while a slower shot with greater spin could enter rolling mode (\( e_x = 0 \)) or grip the surface (\( e_x > 0 \)). Generally during low incidence angles, a ball slides throughout impact with a consistent friction to normal force ratio. Increased incident angles cause the frictional force to drop to zero and reverse during impact (Cross, 2002a).
Haake & Goodwill (1997) state that low pressure balls generally rebound slower and steeper than highly pressurised balls, attributing these differences to smaller ball deformations that cause balls to slip throughout impact.

**Measurement Techniques**

Recent improvements in high-speed photography have made it a popular method for evaluating impact properties such as ball speed, spin, and contact time. Ball rebound and spin has been measured at 100 frames per second (fps) for low speed impacts and 200 fps for higher speed impacts (Cross, 2003b; Goodwill & Haake, 2004b; Groppel et al., 1987). Cotter (2002) used a long duration flash and multiple exposure camera to capture several images of ball rebound position and orientation. Contact time has been measured at 4000fps and 30,000fps (Groppel et al., 1987; Haake et al., 2003). Additionally, impact and rebound speed for normal impacts has been measured using lightgates (Cotter, 2002; Davies, 2005; Haake et al., 2003).

Several analytical models have been developed to assess ball stiffness and damping properties during impacts. Dignall & Haake (2000) developed a viscoelastic ball model with a spring-damper system such that the stiffness, $k_s$, and damping, $c$, can be determined from the contact time and inbound and outbound velocities as shown in Equations 2.2 and 2.3. This ball model has also been used as part of more complicated racket and stringbed impact models (Goodwill & Haake, 2001).

$$k_s = \frac{m \pi^2}{T_c^2} \quad (2.2)$$

$$c = -\frac{2m}{T_c} \ln \left( \frac{V_{out}}{V_{in}} \right) \quad (2.3)$$

Babitsky & Veprik (1998) developed an analytical method to fit a similar viscoelastic model directly to the force-time curve obtained during a force plate impact. Davies (2005) applied this method to tennis ball impacts to determine stiffness and damping properties for a range of tennis balls and impact speeds. A more complex model, incorporating a second damping component, has also been developed using experimental data and a convergence technique (Goodwill & Haake, 2004c).

### 2.2.2 Ball Flight

While impacts determine the initial conditions imparted to a ball, the majority of its time during play is spent in flight. Some sports balls, like bowling balls and shot puts, have enough momentum to overcome drag forces. Tennis balls, however, lack the mass to do this, making airflow patterns and drag forces around the ball more important in overall performance. The drag force on an object, shown in Equation 2.4, is dependent on a specific non-dimensional drag coefficient, frontal area, fluid velocity, and fluid density. The Reynolds number, shown in Equation 2.5, is dependent on similar values, as well as the fluid viscosity and ball diameter.

$$F_D = \frac{1}{2} C_D A v^2 \rho \quad (2.4)$$

$$Re = \frac{\rho v D}{\mu} \quad (2.5)$$

A ball moving slowly through the air experiences laminar airflow, a condition where the pressure forces around the ball are balanced and have no effect on the ball's motion. As there is no pressure drag on a projectile at these speeds (laminar flow occurs where $Re < 2,000$), the entire drag force can be attributed to viscous (skin-friction) drag acting tangential to the ball's surface. When the Reynolds number exceeds roughly 100,000, the boundary layer becomes turbulent and is no longer slowed by viscous drag, but from pressure drag and forces normal to the body's surface (Bloomfield, 1997). By measuring the drag force...
with variations in flow speed, differences in drag coefficients and airflow can be determined according to Figure 2.3.

Mehta & Pallis (2001b) examine a variety of sports balls and the effects of surface roughness on their aerodynamic properties. A laminar boundary layer on a ball can be 'tripped' into early transition to improve flight using a protrusion, like the seam on a baseball or cricket ball, or differences in surface roughness, like the dimples on a golf ball and the fuzz on a tennis ball. These surface characteristics are important when considering desired ball play properties.

Achenbach (1974) developed a roughness parameter for spheres using the height of roughness elements and the sphere’s diameter to examine the effects of surface roughness on drag forces. Figure 2.3 shows that the critical $Re$ value and drag coefficient both decrease as surface roughness increases. This drop in drag makes it important to ensure sports balls are in the supercritical flow regime either through increased ball speed or a lowered critical Reynolds value from surface roughness elements.

![Figure 2.3: Flow properties on smooth and rough spheres.](image)

Given the importance of surface characteristics with respect to aerodynamics in other ball sports such as cricket and golf, it is no surprise that tennis balls, with their porous cloth covering, provide a surface with varying drag properties (Beasley & Camp, 2002; Mehta, 2000). The flight performance of a tennis ball influences not only how much a given shot will slow due to drag, but also the reaction time an opponent has to return the shot. Lower drag coefficients and drag forces allow the ball to reach its destination more quickly, forcing opponents to react accordingly. A summary of work on stationary tennis balls is presented in Table 2.6. Tested wind speeds range from 10-60ms$^{-1}$, though higher $Re$ values were also obtained using larger prototype balls at slower wind speeds.

Cooke (2000) states that the primary drag mechanism on a ball is due to pressure drag and its combination with skin friction. Calculations also indicate that the initial transient stage in the ball’s flow pattern after impact can be considered negligible. While a ball’s drag coefficient is independent of Reynolds number, it is dependent on skin friction caused by surface irregularities from the cloth. Alam et al. (2003) found that seam orientation affects drag values at low Reynolds numbers, but was negligible at higher values. Cooke (2000) attributes experimental $C_D$ differences to varying methods in ball measurement as Chadwick & Haake (2000a) include the projected nap height in calculations, while Haake et al. (2000a) do not. Streamlines show a raised nap causes the boundary layer to separate earlier and create a larger wake behind the ball, as well as higher drag values.

Mehta & Pallis (2001a) detail the role of ball fuzz in tennis ball aerodynamics. Fuzz drag is proposed to explain higher $C_D$ values at lower $Re$ values, an observation not typical within the supercritical and
Table 2.6: Aerodynamic characteristics of static tennis balls.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Balls Used</th>
<th>Reynolds Range</th>
<th>Drag Values</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alam et al. (2003)</td>
<td>Wilson (US Open, DC2, Rally 2), Slazenger, Hydroguard, Ultra Vis 1 and 4, Bartlett</td>
<td>50,000 - 170,000</td>
<td>0.57 - 0.71</td>
<td>Seam orientation important at very low Reynolds numbers.</td>
</tr>
<tr>
<td>Haake et al. (2000a)</td>
<td>standard, pressureless, oversized, raised, worn naps</td>
<td>200,000 - 280,000</td>
<td>0.52-0.54, 0.51-0.60</td>
<td>Manually raised, electrically shaved. Differences in $C_D$ up to 10%.</td>
</tr>
<tr>
<td>Stempak (1988)</td>
<td>new Tretorn</td>
<td></td>
<td>0.51-.79</td>
<td>Drag coefficient independent of linear velocity</td>
</tr>
<tr>
<td>Chadwick &amp; Haake (2000a)</td>
<td>fluffed, standard, pressureless, shaved nap, larger</td>
<td>200,000 - 270,000</td>
<td>0.50 - 0.57</td>
<td>$C_D$ of unmodified balls at 0.53. Differences up to 6% with shaved and manually raised balls.</td>
</tr>
<tr>
<td>Mehta &amp; Pallis (2001a)</td>
<td>core, larger prototype, new, 3-9 games, US Open, electric/razor shaved</td>
<td>167,000 - 284,000</td>
<td>0.55-0.63, up to 0.70</td>
<td>Larger prototype was 11” ball. Rubber core had $C_D$ of 0.50. Discusses role of fuzz orientation at higher speeds.</td>
</tr>
<tr>
<td>Sayers (2003)</td>
<td>larger prototype</td>
<td>50,000 - 200,000</td>
<td>0.50 -0.60</td>
<td>Larger ball reduced error in force measurements.</td>
</tr>
<tr>
<td>Goodwill et al. (2004)</td>
<td>range of brands and wear conditions</td>
<td>80,000-250,000</td>
<td>0.62-0.66</td>
<td>No significant differences between brands. 1500 impacts lowered $C_D$ by 0.04.</td>
</tr>
</tbody>
</table>
transcritical regimes where values are expected to increase after the critical $Re$. Ball fuzz leads to increased $C_D$ values at lower speeds as the filaments are nearly vertical and therefore susceptible to pressure drag. Higher speeds force the filaments to lie down, as shown in Figure 2.4. The authors also observe that stiffer filaments have a lower dependence on $Re$ as their orientation is not as affected by wind speed.

![Figure 2.4: Example of fuzz orientation at low and high speeds (Mehta & Pallis, 2001a).](image)

Stationary ball testing has its limitations, however, as tennis is a game dependent on spin for shot control and ball placement. Rotation affects a thin layer of air around the ball due to its interaction with the oncoming air stream, causing differences in the location of air separation. The air must then travel more quickly around one side of the ball than the other, creating lift from pressure differences according to Bernoulli’s principle where increased fluid speed creates lower pressure. Bloomfield (1997) attributes forces generated by spinning balls to both the Magnus force, caused by pressure differences, as well as a wake deflection force created by differences in airflow separation around the ball.

Stempanek (1988) modelled spinning tennis balls to examine the ratio of the rotational and linear velocities ($S$) with respect to the drag and lift coefficients. Although the rotational values are realistic, the linear air speeds are limited and may not fully capture the effects of fuzz orientation and drag during play. Sayers (2003) examined a more realistic range of ball speeds and spins and found that both the lift and drag coefficients increased with an increase in the spin to linear velocity ratio. While the drag measurements were comparable with previous authors, the lift values were noticeably higher due to his use of an oversized prototype ball. The author suggested that the Magnus effect induced by ball spin could mask any differences in lift and drag forces. The Magnus force is a result of unbalanced pressure on the surface of a spinning ball due to velocity differences and Bernoulli’s principle.

The importance of ball speed and spin in the game of tennis has forced recent research to examine conditions more representative of the modern game. Recent aerodynamic spinning studies have incorporated testing at wind speeds up to 60ms$^{-1}$ and spin rates up to 3000rpm. This work is summarised in Table 2.7.

**Measurement Techniques**

A range of measurement methods have been used in previous work to assess the aerodynamic properties of tennis balls. Testing has utilised large scale automotive tunnels (Alam et al., 2004), open-jet return circuit tunnels (Mehta & Pallis, 2001a; Sayers, 2003), and slotted-wall test sections (Goodwill et al., 2004). Force measurements have been recorded on a two component balance (Goodwill et al., 2004), a three component balance (Chadwick & Haake, 2000a), and a six-component balance (Alam et al., 2004). Balls have been supported from behind, in the wake of the ball (Chadwick & Haake, 2000a; Sayers, 2003), spun on a single support sting (Alam et al., 2004), and spun using two side mounted support stings (Goodwill & Haake, 2004a; Goodwill et al., 2004; Sayers, 2003).

Another method of assessing the differences in ball flight on the game is a trajectory simulation based on the aerodynamic properties of the ball and standard equations of motion. While examining the feasibility of using a larger ball to slow the game, Haake et al. (2000a) calculated that the Type III ball has a wider range of acceptable serves due to increased drag and slower travel times. Simulations indicated a 200mm difference in court impact position from a ball with a raised or lowered nap (Chadwick & Haake, 2000a).
Stempanek (1988) used trajectory simulation to examine the effects of increased spin rates and showed that with increased rotational velocity, the ball reached its destination more quickly - forcing the opposing player to react more quickly. While there have been some attempts to determine the effects of the changed ball nap due to wear, there has been little attention paid to possible differences in the ball-court interaction and initial applied velocity and spin differences resulting from wear.

2.3 Player Perception

Absolute measures of ball performance are often tempered by subjective measures like feel and comfort that are perceived by the athlete during competition. With experience, players associate ball brands with differing playing properties and degradation characteristics. Hocknell et al. (1996) and Roberts (2002) examine the role of feel in a golf shot, finding indirect aural and visual feedback play an important role in player perception of shot quality along with direct feedback through contact with the club. The lack of correlation between golfer shot perception with experimental and theoretical ball-club impacts also suggests player opinions are influenced by sensory feedback such as impact sound (Roberts et al., 2001). This section looks to review areas influencing player perception and determine areas important to consider in future work.

2.3.1 Feel in Tennis Ball Impacts

Goodwill & Haake (2000) used the coefficient of restitution to characterise feel off the racket, but did not correlate testing results with player perceptions and preferences. Haake & Goodwill (2002) define feel for a tennis ball impact using the coefficient of restitution in combination with the dynamic stiffness of the ball. A ball with ‘better feel’ has higher coefficient of restitution and dynamic stiffness values. Although this method produced intuitively correct results, supportive player testing has not yet been conducted.

Davies (2005) conducted a thorough investigation into tennis ball feel. An initial study examined components of ball feel rising from all areas of play, while subsequent experimentation focused on vibration and sound during impact. Key areas identified by Davies are shown in Table 2.8. Players determined that control of the ball in the air, control off the racket, and a consistent bounce were the most important areas resulting from this study. Stiffness and damping properties did not predict ball feel and when impact sound was removed, players showed a diminished ability to distinguish between balls.

Harder balls were perceived to be louder, faster off the racket, and possess a shorter, higher pitched sound. Heavy balls appeared to be slower off the racket with a longer impact sound. Louder and higher pitched balls were associated with a loss of control and players felt low vibration balls were more pleasant.

<table>
<thead>
<tr>
<th></th>
<th>$C_D$ trends</th>
<th>$C_L$ trends</th>
<th>Other notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sayers (2003)</td>
<td>Independent of $Re$, increase with higher $S$.</td>
<td>Independent of $Re$, increase with higher $S$.</td>
<td>Used 11&quot; ball in testing. Values noticeably higher than found with standard sized balls.</td>
</tr>
<tr>
<td>Goodwill et al. (2004)</td>
<td>Increase with higher $S$ (0.64-0.69), $Re$ dependent. Average difference of 0.04 for heavily worn ball.</td>
<td>Increase with higher $S$, $Re$ dependent for $S &lt; 0.1$. Differences in worn balls between $0.05 &lt; S &lt; 0.15$</td>
<td>Smaller differences between new and worn balls at higher wind speeds due to fuzz orientation. Spinning causes fuzz to lift from surface.</td>
</tr>
<tr>
<td>Alam et al. (2004)</td>
<td>Increase with increase in spin speed (0.00-0.30). Lift force increases with increase in spin rate.</td>
<td>Rotational speed can play a significant role at lower speeds, differences in orientation of fuzz during spin at higher speeds.</td>
<td></td>
</tr>
<tr>
<td>Goodwill &amp; Haake (2004a)</td>
<td>Difference of 0.4 for spinning and stationary worn balls.</td>
<td>Lower $C_L$ for worn balls with $S &lt; 0.2$.</td>
<td>New and worn balls have the same diameter, differ only in surface condition.</td>
</tr>
</tbody>
</table>

Table 2.7: Spinning investigations into ball aerodynamics.
Table 2.8: Important areas in ball feel (Davies, 2005).

<table>
<thead>
<tr>
<th>Ball characteristic</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight</td>
<td>Speed, adjustment to flight trajectory, weight, ability to control flight, ball compression</td>
</tr>
<tr>
<td>Bounce</td>
<td>Bounce height, compression, weight, effect of bounce on shot selection, bounce characteristics, effect of spin on bounce</td>
</tr>
<tr>
<td>Feeling from impact</td>
<td>Hardness, weight, feel of ball on racket, feeling in arm, feel of ball behaviour</td>
</tr>
<tr>
<td>Sound</td>
<td>Sound descriptors, loudness, differences due to ball type, effect of sound, impact location</td>
</tr>
<tr>
<td>Appearance</td>
<td>Size, visibility, ball ridges, sphericity, ball cloth</td>
</tr>
<tr>
<td>Player psychology</td>
<td>Effect of brand name, effect of blanking logo on ball, positive and negative responses</td>
</tr>
<tr>
<td>Wear</td>
<td>Ball pressure, ball stuffing up, ball losing cloth, effect of court on ball wear, perceptions of durability</td>
</tr>
</tbody>
</table>

Testing indicated that only skilled subjects were capable of fine discrimination between balls. Reliable subjects associated increased vibration at the grip with a less pleasant, harder, heavier ball having increased speed.

2.3.2 Ball Play Properties

An investigation by Pallis (1999b) characterised ball speeds in professional tennis, a summary of which is presented in Table 2.9. The speed of the ball throughout the course of each shot is specified, with noticeable differences between the beginning and end of a shot.

When considering impact testing speeds, consideration must also be given to racket velocities. Elliott & Marsh (1989) documented racket pre-impact speeds of 26.5ms\(^{-1}\) and 16.6ms\(^{-1}\) for forehand topspin and backspin shots. Takahashi et al. (1996) examined racket motion perpendicular to, and in the direction of, ball motion, finding racket speeds of 18.6ms\(^{-1}\) and 18.3ms\(^{-1}\) for flat and topspin forehand shots. The relative velocities of the racket and ball are greater than the final shot speeds listed, and this difference should be accounted for during impact testing. Pallis (1998b) also characterised ball spin for a range of shots at the 1997 US Open. These values, shown in Table 2.10, will be used as a guideline for evaluating measured spin rates and perceived differences in ball spin.

2.3.3 Player Ability

During play, players often use ball appearance as an indicator of performance and sustained wear when selecting a ball for service. Players relying on a hard serve will want a ball with a smaller area and less fuzz, as it will undergo a smaller change in speed throughout the course of a shot - perhaps making the difference in a successful return. The effects of flight differences due to ball degradation will rely on player reaction abilities.

Chow et al. (1999) and Andrew et al. (2003) independently determined reaction times from initial ball launch to racket movement in tennis volleys of around 200ms. Results suggest skilled players can complete a shot in less than 600ms for a quickly hit ball, with the ability to react even more quickly by interpreting visual cues from their opponent. Both authors found increases in movement times with slower ball speeds, indicating players react and perform more quickly with faster ball speeds. Neither study investigates potential thresholds regarding reaction times and maximum ball speeds. Haake et al. (2000b) determined that serves above 45ms\(^{-1}\) (100mph) begin to have an effect on a player's ability to return a serve for semi-professional players, but that this threshold likely increases with player ability. Brody (2004) stated that serves over 74ms\(^{-1}\) (165mph) within reach of the returner are impossible to return based on reaction time data, though speeds of 54ms\(^{-1}\) (120mph) can also be difficult to return if well placed.
Table 2.9: Summary of shot speeds (ms⁻¹) determined from Pallis (1999b).

<table>
<thead>
<tr>
<th>Shot</th>
<th>Pre-hit speed</th>
<th>Max speed after hit</th>
<th>Pre-bounce speed</th>
<th>Post-bounce speed</th>
<th>End speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serve</td>
<td>52.88</td>
<td>38.34</td>
<td>27.32</td>
<td>23.80</td>
<td></td>
</tr>
<tr>
<td>Forehand return</td>
<td>26.44</td>
<td>28.65</td>
<td>17.63</td>
<td>13.22</td>
<td>10.58</td>
</tr>
<tr>
<td>Backhand return</td>
<td>21.15</td>
<td>22.48</td>
<td>14.10</td>
<td>9.25</td>
<td>7.93</td>
</tr>
<tr>
<td>Forehand</td>
<td>8.37</td>
<td>33.49</td>
<td>21.59</td>
<td>14.98</td>
<td>13.66</td>
</tr>
<tr>
<td>Backhand</td>
<td>7.49</td>
<td>30.41</td>
<td>21.59</td>
<td>14.10</td>
<td>12.34</td>
</tr>
<tr>
<td>Forehand volley</td>
<td>16.75</td>
<td>20.71</td>
<td>13.66</td>
<td>9.70</td>
<td>8.37</td>
</tr>
<tr>
<td>Overhead</td>
<td>11.02</td>
<td>48.48</td>
<td>39.22</td>
<td>27.32</td>
<td>23.80</td>
</tr>
</tbody>
</table>

Table 2.10: Ball spin in pro tennis (Pallis, 1998b).

<table>
<thead>
<tr>
<th>Shot</th>
<th>Recorded spin (rpm)</th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topspin forehand</td>
<td>833-3751</td>
<td>417-3488</td>
<td></td>
</tr>
<tr>
<td>Topspin backhand</td>
<td>790-3333</td>
<td>375-2143</td>
<td></td>
</tr>
<tr>
<td>Backspin forehand</td>
<td>1500-3488</td>
<td>1667-3750</td>
<td></td>
</tr>
<tr>
<td>1st serve</td>
<td>1000-4284</td>
<td>357-3947</td>
<td></td>
</tr>
<tr>
<td>2nd serve</td>
<td>2830-5357</td>
<td>882-4284</td>
<td></td>
</tr>
<tr>
<td>Forehand return</td>
<td>600-3751</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Backhand return</td>
<td>714-2055</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

Beginning and skilled players exhibit differing visual search strategies that affect how quickly the ball is processed during play (Fleury et al., 1986). Jones & Miles (1978) find support for their hypothesis that experienced players can 'read the signs' better than inexperienced players after evaluating predictions of tennis ball impact locations while receiving a service. As differences in cue processing can affect the success of shot return, weaker players will benefit more from increased ball flight time.

2.3.4 Player Psychology

Despite engineering and design excellence, consumer products will always be subject to perceived product attributes. Influences such as previous brand experience and associations of product quality will inevitably influence player attitudes towards ball performance and degradation properties. Sensation and perception are also important considerations in understanding the information players gather from tennis balls during play.

Previous Experience

Garvin (1984) suggests "perceptions of quality can be as subjective as assessments of aesthetics." Players develop unique preferences with regards to ball condition and brand from positive and negative playing experiences. Bevan (1995) provides a good analysis with regards to product usability:

This definition is in terms of the characteristics of a product. To the extent that user needs are well-defined and common to the intended users it implies that quality is an inherent attribute of the product. However, if different groups of users have different needs, then they may require different characteristics for a product to have quality, so that assessment of quality becomes dependent on the perception of the user.

Branding serves as an important source of product discrimination and quality determination, notably in oft purchased commodities with limited differentiation like tennis balls (Kohli & Thakor, 1997). As a product characteristic recognised through experience, quality can be separated into four categories (Garvin, 1984):
**Product Quality** An inherent characteristic of the product determined by the presence or absence of measurable product attributes.

**Manufacturing Quality** A product which conforms to specified requirements.

**User Perceived Quality** The combination of product attributes which provide the greatest satisfaction to a specified user.

**Economic Quality** A product which provides performance at an acceptable price, or conformance to requirements at an acceptable cost.

Garvin (1987) developed eight critical categories of quality, shown in Table 2.11. Depending on the product examined, these can either be mutually strengthening or require tradeoffs between dimensions. Classification and applications to tennis balls are also discussed, though this thesis will focus only on aspects of product and user perceived quality. While poor production standards and product consistency will affect player perception of a given brand, these factors are the responsibility of the manufacturer.

**Sensation and Perception**

Sensory product attributes relate to those assessed by the senses: taste, smell, sight, touch, and sound, with the latter three particularly relevant to tennis balls during play. Schiffman (2000) develops a chain of sensory perception from an individual’s response to a given stimulus. Responses to a given stimulus differ because of variations in sense organ sensitivity and processing by the brain. Playing experience will affect individual player responses to these attributes.

\[
\text{stimulus} \rightarrow \text{sensation} \rightarrow \text{perception} \rightarrow \text{response}
\]

Perception in this thesis will focus on ball sight, sound, and touch attributes. Although anecdotal evidence suggests an initial ‘new ball smell’ when tins of pressurised balls are opened, smell was not considered due to the limited influence of this perception during play. Weber’s Law states that the size of the just noticeable difference in a sensation is related to the size of the stimulus (Coren et al., 2004). This proportion determines the magnitude of the noticeable difference using the Weber fraction, which ranges from 0.020 for lifted weights, 0.048 for sound intensities, to 0.079 for light intensities. Perceived brightness has a nonlinear response to stimulus intensity as shown in Equation 2.6. This means that small differences in perceived ball brightness require significant increases in actual ball brightness (Coren et al., 2004). Brighter stimuli have indicated improved reaction times of approximately 28ms when compared to dull stimuli (Grice et al., 1979).

\[
\text{perceived brightness} = (\text{stimulus intensity})^{0.33} \quad (2.6)
\]

Davies (2005) found players to be more inconsistent in ball differentiation when they were prevented from hearing impact sounds. Higher pitched balls were associated with unpleasant responses from players. Touch in tennis balls will affect perceptions of size, texture, stiffness, and mass. These characteristics will be determined from manufacturing variabilities, core constructions, and ball degradation. Player sensitivity to tactile attributes will likely be observed during the service, as this is the only shot where players can touch the balls. An example of a player examining balls for service is shown in Figure 2.5.

![Figure 2.5: Player selecting balls for service during the 2006 French Open.](image)
Table 2.11: Quality attributes from Garvin (1987) applied to tennis balls.

<table>
<thead>
<tr>
<th>Quality Attribute</th>
<th>Classification</th>
<th>Description</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Product</td>
<td>Reference to a product’s primary operating characteristics.</td>
<td>Cloth aerodynamic properties, implied performance from appearance.</td>
</tr>
<tr>
<td>Features</td>
<td>Product</td>
<td>Characteristics that supplement basic product functioning.</td>
<td>Cloth dye features (brighter, more visible; water-resistant), core characteristics.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Manufacturing</td>
<td>Probability of product malfunctioning within a given time period.</td>
<td>Poorly manufactured batches will affect other attributes such as performance, durability, aesthetics, and perceived quality.</td>
</tr>
<tr>
<td>Conformance</td>
<td>Manufacturing</td>
<td>Design and operating characteristics meet established standards.</td>
<td>No established technical standards for cloth covering; manufacturer standards will dictate product conformance. ITF standards.</td>
</tr>
<tr>
<td>Durability</td>
<td>Economic and user perceived</td>
<td>Measure of product life (economic and technical).</td>
<td>How long a ball will be perceived acceptable for play (and meet ITF standards); the cost and timing of replacement.</td>
</tr>
<tr>
<td>Serviceability</td>
<td>Manufacturing</td>
<td>Speed, courtesy, competence, and ease of repair.</td>
<td>Manufacturer response to poor quality samples.</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>User perceived</td>
<td>How a product looks, feels, sounds, tastes, or smells - usually subject to individual preference.</td>
<td>Focus on look and tactile feel of ball condition.</td>
</tr>
<tr>
<td>Perceived Quality</td>
<td>User perceived</td>
<td>Product reputation.</td>
<td>Role of branding and ball logo on player perception of quality.</td>
</tr>
</tbody>
</table>
2.3.5 Sensory Evaluation Techniques

Sensory evaluation techniques are used to determine the quality of a given product for use or consumption. These qualities are generally difficult to assess by other means. Standard methods of measure are summarised below along with strengths and weaknesses in their application (Meilgaard et al., 1999).

Classification Samples are grouped. This provides the least amount of information with nominal data.

Grading Samples are evaluated by expert graders and given an overall rating based on the attributes present. This method requires expert graders.

Ranking Samples are placed in order of intensity regarding a given attribute. Ordinal data can be analysed by non-parametric tests which requires relatively little training time, but difficulties in attribute differentiation are possible.

Scaling Numbers and words are used to express the intensity of an attribute. Scaling is capable of providing ordinal, interval, and ratio data that can be analysed by parametric and non-parametric tests. It is dependent on a scaling system broad enough to capture attribute range and discrete enough to distinguish between samples. Other important considerations include the degree to which the assessment panel is taught to associate a given sensation with the attribute in question and that the panel uses the scale the same way across all the samples and over time.

Several methods have been used in previous perception work. Davies (2005) uses paired comparisons, a subset of ranking methods, to determine subtle differences in impact properties during tennis ball impacts. Roberts (2002) uses a scaling system to evaluate golfer perceptions of tactile and auditory properties of golf clubs. Paired comparison techniques have also been used in auditory golf analyses (Barrass et al., 2006).

2.4 Ball Degradation in Tennis

Professional tournaments strictly regulate the lifespan of balls used in competition, even forcing fans to return balls to the court when balls are hit into the stands. This is due not to the cost of the ball, but the effect it would have on the game.

The American Society for Metals defines impact wear as wear due to repetitive exposure to dynamic contact by another solid body (Engel, 1992). Parameters important in the wearing process include loads, materials, surface definition, and wearing coefficients. The volume worn away during linear impact in an abrasive sliding process is related to the product of the wear coefficient, normal contact force, and sliding distance divided by the hardness of the wearing body. Ludema (1992) examines sliding and adhesive wear and specifies the wear rate equation as the product of the wear coefficient, applied load, and sliding speed, divided by the hardness of the softest pair of materials. While these definitions do not directly apply to all areas involved in tennis ball wear, differences in wear coefficients between brands and cloth types, normal impact forces, contact distance, and speeds can be relevant to many aspects of ball wear.

Noticeable differences in the dynamic COR for balls used in simulated wear testing occur between 50 and 100 impacts, with negligible differences between pressurised and pressureless balls. Higher testing speeds (40ms⁻¹) showed greater differences in COR values for worn balls (Miller & Messner, 2003). With regards to standardised testing, forward and return compression values were found to increase with additional impacts, though bounce height was not significantly affected. The rate of mass loss for a traditionally covered sateen weave ball slows after initial losses, while a needle felt ball maintains a linear trend with continued mass loss and localised wearing (Capel-Davies & Miller, 2003). Initial losses in sateen weave cloth are hypothesised to be the plucking of the raised, loose fibres created during manufacture. Continued mass losses in needle felt are likely to result from its construction.

Rand et al. (1979) investigate the effects of repeated impacts and natural ageing on three brands of pressurised tennis balls. The balls all bounced higher in a standard drop test after 800 impacts than
they did fresh from the can. The authors attribute this increase to lowered aerodynamic drag during the drop test from nap loss. Both the impacted balls and a control group produced relatively consistent performance over five days of bounce evaluations, but after this point performance noticeably deteriorated. These results suggest that the time out of the container plays a more significant role in performance than repeated impacts. While work has been pursued to use low-permeability gases in ball cores to improve ball life, these gases altered ball impact sound and utilised harmful refrigerants and hydrocarbons (Reed & Thomas, 1988).

There is a generally accepted hypothesis in tennis that it is advantageous to serve with newer balls. In an examination of men’s and women’s singles data during the 2000 Australian Open, Norton & Clarke (2002) determined there are no consistent trends among service and point data. There is little evidence that ball age affects any serving statistics. Further statistical analysis of tennis point and service data was also performed at Wimbledon by Magnus & Klaassen (1999). Men’s singles data provided no evidence for point differences between new balls and those used for nine games, though the women’s data showed a significantly lower probability for winning a point with a ball used for nine games than a new ball. The probability of a successful first serve also increased with older balls, suggesting the ball is easier to control with increased use.

Figure 2.6 displays changes to standardised test results after play on three different court surfaces. While the forward and return deformation differences are similar for each of the surfaces, the acrylic surface produced noticeably higher bounce height increases and mass losses (ITF, 2006a).

Figure 2.6: Effects of playing surface on standardised test results for used balls.

Davies (2005) determined that ball wear has the potential to affect other areas of ball feel, most noticeably the flight of the ball as it fuzzes up or loses cloth. He also found that balls that feel slower would tend to be hit harder by players, increasing impact forces on the ball, as well as the potential for injury.

### 2.4.1 Characteristics of Rubber

Rubber fatigue can result in a change in stiffness and a loss of mechanical strength (Brown, 1996). Fatigue life and toughness are related to the energy required to break the elastomer chains. Extended rest also causes rubber to become sluggish, so it must often be worked before it behaves normally (Nauton, 1954). This can be seen in the pre-compression required of tennis balls before testing. Rubbers with lower permeability to air also tend to be less resilient (Reed & Thomas, 1988).

In squash balls, increased temperatures produce higher COR values with more noticeable differences at lower impact speeds (Chapman & Zuyderhoff, 1986). Rose et al. (2000) found that pressurised tennis balls are most affected by lower temperatures because they depend on a pressurised core for their bounce characteristics. Compression and dynamic COR measurements show a smaller dependence on temperature, though like the squash balls, there were slight tendencies for increased COR at higher temperatures.

Brown (1996) discusses the permeation of a gas through rubber in two steps: the gas dissolving into the rubber and then the dissolved gas diffusing through the rubber. Permeation varies with temperature.
and can depend on test piece thickness and pressure differential, suggesting pressurised balls undergo their most rapid pressure loss soon after they are opened.

2.4.2 Characteristics of Cloth

The wool and nylon fibre mix found in tennis ball cloth is used because both fibres possess desirable properties for the cloth's performance. Wool can be felted and mechanically raised to entangle and produce the desired surface texture for ball cloth, while nylon adds increased strength and improved durability. Morton & Hearle (1975) show the work of rupture for nylon is nearly double that of wool, with a much higher breaking strength. Wool, along with other protein fibres, possesses much greater extensibility when under strain.

Wear and abrasion are known to cause fuzzing and pilling on fabrics. As the fabric begins to wear due to mechanical action, small fibres begin to protrude from the surface. These fibre ends continue to fray and break into smaller fibres, forming a fuzzy appearance on the fabric. When the fuzz on the fabric surface reaches a certain level from continued wear, the frayed ends entangle and mat to form pills on the fabric surface, continuing to incorporate nearby fibres. Sustained wear and abrasion cause the pills to wear from the surface (Jensen & Carstensen, 2002). Ginitis & Mead (1959) determined interfibre friction and bending stiffness are important influences in fuzz and pill formation. Nylon shows a greater tendency towards fuzzing due to its high strength, moderate interfibre friction, and low stiffness. Wool, a low tenacity fibre, tends to break and create shorter fuzz. The authors determined critical fibre heights for entanglement of 0.781cm for wool and 0.714cm for nylon and correlate these heights to the stress-strain curves of the fibres. Fibres with the greatest tendency to entangle also had the most vertical curves. The roles of fibre properties in fuzzing and pill formation are shown in Table 2.12.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fibre property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzz formation</td>
<td>Friction, stiffness, breaking strength, abrasion resistance</td>
</tr>
<tr>
<td>Entanglement</td>
<td>Shape, denier, stiffness, recovery, friction, elongation</td>
</tr>
<tr>
<td>Pill Wearoff</td>
<td>Breaking strength, flex life</td>
</tr>
</tbody>
</table>

2.5 Summary of Literature Reviewed

There exists a large body of literature on tennis ball construction, impact properties, and flight differences. Dynamic testing of balls has allowed for a better understanding of ball properties during play, though data for balls sustaining repeated impacts and natural pressure loss is limited. There exists no dynamic testing information focusing solely on changes to the ball's surface condition. Work concerning frictional interactions with court surfaces and racket stringbeds generally does not focus on the ball condition, but on court and string characteristics. Differences due to ball degradation are not considered.

Ball surface condition has been shown to play an important role in aerodynamics and drag in numerous studies, but there exists no method to compare ball conditions between these studies. Ball conditions are only subjectively described, with no real understanding of how these worn balls relate to player perception during play.

Player perception and feel of tennis balls focuses on new balls of differing constructions. There is no information concerning perceptible differences in ball condition and their relationship to physical differences in ball degradation.

The proposed direction of research concerns investigating causes of ball degradation and documenting resulting differences in ball performance and player perception. Additionally, an objective method to compare the surface condition of worn tennis balls is desired to allow comparison amongst future research.
Chapter 3

Digital Fuzziness Metric

This chapter presents work done towards the development and optimisation of an objective measure of tennis ball surface condition. Metric specifications and initial work are discussed before focusing on the selected technique using digital imaging. Three stages of the process are identified and considered for their effects on the final measurement.

3.1 Fuzziness and Tennis Balls

The process of fuzzing and pilling in fabrics has been shown to occur in steps (Baird et al., 1956; Gintis & Mead, 1959). Gintis & Mead (1959) describe pilling in three stages for fabrics: fibres surface as a result of mechanical action; the surface fibres tangle and mat into pills; and finally the pills are worn or pulled from the surface. Pilling results from abrasion of the fabric during wear and normal use. Fabrics made from high strength, low stiffness materials like nylon, are prone to fuzzing and entanglement. Natural fibres such as wool tend to break and contribute towards shorter fuzz on the fabric surface.

In tennis balls, raising is part of the production method as the cloth is stretched, teased to draw out fibres, and then uniformly clipped to a given height. While giving the fabric the desired appearance and initial play properties, raising also serves to reduce fabric strength as fibres are pulled from the internal fabric structure, making it more sensitive to abrasive court and racket impacts. For tennis balls, four major conditions have been identified according to the fuzzing and pilling process. With wear, fibres from the surface of a new ball are lifted to form a fuzzy ball with loose fuzz, shown in Figure 3.1(b). These fibres entangle and form tufts on the ball’s surface. A tufted fuzz ball is shown in Figure 3.1(c). Finally these pills wear from the ball’s surface to create a bald ball similar to that shown in Figure 3.1(d).

Elite players are very selective when choosing balls as it is generally believed that it is advantageous to serve with new balls. Although data collected during the 2000 Australian Open indicates little evidence that ball age affects any serving statistics, interviews conducted with elite players indicate noticeable differences in ball performance and changes to ball fuzziness during match play (Norton & Clarke, 2002).

![Figure 3.1: Tennis balls in varying states of wear.](image-url)
Some players consider a limited degree of fuzz desirable, as it improves control and allows more time to complete strokes, whereas others find it hinders ball speed and their ability to win points (Loughborough University Tennis Team, 2004). Excessive fuzziness can occur from manufacturing process variability, court and racket interactions, and environmental conditions.

While much work has been done to characterise aerodynamic performance differences in tennis balls, there is no method to objectively compare differences in ball condition between studies (Chadwick & Haake, 2000a; Haake et al., 2000a; Mehta & Pallis, 2001a). Capel-Davies & Miller (2003) document mass loss using a durability test rig but give no indication of ball surface condition throughout testing.

There is no quantitative measure to assess the role of ball fuzziness and current inspection methods by manufacturers include comparison to standardised visual images of cloth wear for a qualitative rating of ball fuzziness. With documented differences in ball performance and player interviews indicating noticeable differences in perceived performance, there is a need to develop an objective measure of ball surface condition. A metric for ball fuzziness will allow performance and perception data from varied testing setups to be compared and analysed.

### 3.1.1 Measuring Cloth Degradation

There are a large number of methods documented by the British Standards Institute, the American Society for Testing and Materials, and the International Standards Organisation that determine abrasion resistance, pilling, and general wear based on a visual comparison of worn test samples to known reference images (ASTM, 2002a,b,c; BSI, 2000). Unfortunately, however standardised, these methods still rely on subjective visual comparisons to pre-existing image samples.

The Kawabata Evaluation System is well known within the textile industry as a standardised method of evaluating compressive, bending, shearing, and tensile stiffness, along with surface characteristics like smoothness and friction (Kawabata, 1980). This system has the potential to predict human response and evaluate how individual textile variables affect the perception of softness. Instrumentation and measurements, however, require 20×20cm flat test pieces that will be unavailable with tennis balls used during play. Due to the cost and difficulties of modifying existing instrumentation effectively, this method was not pursued further.

A variety of roughness measurement techniques have been successfully applied to the complicated surface texture of textiles. Sharply pointed stylus tracers are used to produce roughness profiles and calculate standardised measures of roughness (Thomas, 1974). Optical measurements prove to be a major advantage as there is no contact with the fabric surface (Ramgulam et al., 1993). Bueno et al. (2000a,b) use variation in light absorption between fabrics to differentiate their surface harshness, but find these methods are sensitive to fabric colour and dye.

Advancements in digital imaging have made it a popular technique in new methods of evaluating surface roughness. Fourier analysis can be used to determine weave patterns and fuzz on the fabric (Jensen & Carstensen, 2002; Xu, 1996). Hu et al. (2002) use fractals to classify the roughness of fleece fabric, finding good correlation with human subjective grading, though Sakaguchi et al. (2001) do not find human evaluations in agreement with the coefficient of variation and power spectra derived from digital images. Texture analysis of greyscale images has also produced good methods of roughness evaluation by analysing pixel distributions and distribution statistics (Chappard et al., 2003; Kiran et al., 1998; Presley, 1997).

Hsi et al. (2000) develop a technique using digital imaging to analyse fuzz detected in digital images of textiles and assess reasonable measures of fuzz characterisation. Images are processed to highlight the desired fuzz for analysis from a binary image. The fuzz on the images was broken up into three categories and then analysed based on the distribution.

Differences in construction and surface pile can also affect the frictional behaviour of fabrics. Ajayi (1992) finds a relationship between frictional resistance and fabric structure, though Bueno et al. (1997) find frictional values inconsistent with sanding and raising experiments.
3.1.2 Metric Requirements

Currently, manufacturers evaluate tennis balls on a subjective scale with regards to the condition of the cloth cover. This process is wholly dependent on the person visually inspecting the balls, and no quantitative performance information can be determined. Factors such as the length and number of fibre strands protruding from the ball surface are used to classify ball condition. These factors, however, do not necessarily reflect overall ball characteristics and relate to performance measures and player perception. Several initial design specifications were established as minimum requirements for successful implementation of a fuzziness metric.

**Practicality** The method must be able to be implemented easily in a range of environments.

**Repeatability** The metric must produce consistent results for balls of similar condition and for repeated trials on one ball.

**Significance** The method should relate to ball performance data (e.g. aerodynamic) and player perception of ball condition.

**Ball size independence** The metric must be successful in characterising both standard and oversize balls with regards to their surface condition and not their ball diameter.

3.2 Initial Investigations

Friction coefficients between tennis balls and a variety of surfaces were investigated, but differentiation between balls was limited due to the small magnitudes of the static and rolling values. A standard measure of roughness involves dragging a stylus over a surface to produce a surface profile, recently improved to include a non-contact laser stylus. Unfortunately area and depth restrictions limit the effectiveness of this application to tennis balls as measurement is restricted to relatively small areas and depths less than 300µm. Other applications of digital imaging and texture analysis proved difficult because of the brightness of the ball cloth and differences in colour that occur with wear. These variables made application of some methods ineffective (Chappard et al., 2003; Hu et al., 2002; Xu, 1996).

Rapid prototyping technologies have been aided by the development of a digital laser scanner to quickly scan geometry into a computer file for processing and prototype development. Ball samples were scanned to produce digital models comprised of thousands of points meshed into a ball surface. This model was then compared to a smooth sphere of the average measured ball diameter for a given sample, producing height variations over the ball’s surface. Figure 3.2(a) shows an example of the scanned geometry with surface differences shown in Figure 3.2(b). Several challenges exist in the application of this method:

- Data must be collected over the entire ball surface.
- File size increases dramatically with increased scan resolution, making file storage and processing difficult. High scan resolutions are needed to capture fuzz detail.
- The ball diameter can be measured in several ways, each producing slightly different results. This measured diameter, however, is crucial in the geometric comparison and accurately determining ball surface characteristics.
- Balls are not perfectly spherical yet are compared to a spherical surface. Average deviations could reflect ball out-of-roundness and not cloth differences.

The complexity and cost required for this method curtailed future investigations towards optimising the setup. Initial successes were also found with digital imaging focusing on fabric surface geometry, such as the method developed by Hsi et al. (2000). Future efforts were focused in this direction.
Digital imaging has existed since the 1920's, but has recently become popular with rapid advances in personal computing: higher processing speeds, mass data storage, miniaturisation of components, and high-level programming languages. While film images contain more information than a digital system, digital cameras are now increasingly available with a range of functional features for easy image capture at high-pixel resolutions.

Digital image processing generally focuses in two main areas: human interpretation and machine perception. Image enhancement techniques are used to aide human interpretation by clarifying image characteristics while industrial machine vision performs tasks like automatic character recognition and identifying product defects. Examples of these applications include medical xrays and MRIs, satellite imaging, and automatic license plate recognition.

Digital imaging electronically captures images on a charge coupled device (CCD) covered with photocells that detect small changes in light intensity. These photocells are covered with red, green, and blue filters to produce colour images. Two important factors in image generation are quantisation and sampling as there are a finite number of colours and pixels available for representation in an image (Gonzalez & Woods, 2001).

An image is represented as a matrix with M rows and N columns as shown in Equation 3.1. Each spatial index contains individual pixel colour data. These pixels contain three values reflecting the red, green, and blue colour components of the image. It should be noted that while rows are listed first in image indexing, they are the vertical coordinate of the image and not the horizontal component as typical in other mathematical uses. This matrix format lends itself to systematic processing and easy data access.

\[
f(x,y) = \begin{bmatrix}
f(1,1) & f(1,2) & \cdots & f(1,N) \\
f(2,1) & f(2,2) & \cdots & f(2,N) \\
\vdots & \vdots & \ddots & \vdots \\
f(M,1) & f(M,2) & \cdots & f(M,N)
\end{bmatrix}
\] (3.1)

Three digital geometric roughness methods using binary images of tennis balls were identified during initial investigations.

Fuzz density Hsi et al. (2000) develop a fuzz density measure for fabrics by counting the number of fabric pixels in a given portion of the image and dividing by the total number of pixels in the section. The technique is applied to a flat profile of the ball surface.

Sphericity This is a standard shape measure calculated by dividing the minimum observed ball radius by the maximum observed value. In two dimensions, it becomes circularity. This method is applied directly to geometry observed in a binary, outlined ball image.
Roughness profile This method involves applying standard roughness measures, such as mean roughness depth ($R_z$) and arithmetical mean deviation of a roughness profile ($R_a$), to a digital representation of the ball's surface. It can be applied to flattened version of ball surface profile.

While there are many commercially available image processing programs to produce binary images and perform the required image pre-processing, algorithms, along with the image processing, were implemented using Mathworks MATLAB v7.01. MATLAB was chosen as the processing software because of its ability to handle both image processing requirements as well as matrix and mathematical operations. A standard, high-resolution colour digital camera was used during testing due to its easy availability and the rapid progression of current technology to include affordable, high resolution cameras. A mono-CCD camera could also be used to produce greyscale images for analysis. There are three major components in the implementation of a digital fuzziness metric (DFM):

Image capture The physical setup and equipment required to acquire an acceptable image, including camera specifications and additional lighting sources.

Image pre-processing The intermediate processing steps required to produce a binary image like the one shown in Figure 3.8(d).

Algorithm implementation The density and roughness profile methods require the application of a measurement designed for assessing roughness on flat surfaces to be applied to the circular ball profile. This required the conversion from Cartesian to polar coordinates using a centre point to develop a radial surface roughness.

3.4 Image Capture

The image environment must be standardised to ensure consistent image capture, yet still allow feasible implementation in a range of environments. The background must contrast with the object under review to produce an image suitable for thresholding. In this application, a matte black background allowed for easy image segmentation when used with the ball’s yellow cloth. It is also recommended that baffles be used to minimise any additional non-uniform light emitted from other sources. Two main considerations were identified as crucial components of consistent image capture: camera specifications and lighting. A third factor, surface conditioning, is also discussed to ensure repeatable sample presentation. A diagram of the test setup is shown in Figure 3.3.

![Diagram of image capture setup](image)

Figure 3.3: Diagram of image capture setup (not to scale).
3.4.1 Camera and Lens Specifications

Image resolution is an important consideration in assessing the accuracy of the roughness metric. Low resolution images will create difficulties in differentiating samples, while high resolutions will increase processing time and file sizes. In this application, ball samples had an effective resolution of approximately 700×700 pixels, creating roughness measurements ranging from 15-60 pixels. Testing indicated no improvement in ball differentiation with resolutions above this level, though a minimum effective resolution of 600×600 pixels was used.

Different imaging setups, camera resolutions, and zoom lenses will create varied pixel distances for the same surface roughness. To correct for this, a calibration system was set up to turn the pixel distances into standard lengths using a pixel-to-length ratio. A 100mm×100mm grid was constructed using a computer aided design package and printed to scale using a high resolution laser printer. A pixel-to-length ratio was then determined from an image of this grid. Calibration values in this application averaged 110μm/pixel (σ = 5μm), with a suggested maximum value of 150μm/pixel in textile applications such as this one. Acceptable resolution and calibration values were achieved using a standard 5-megapixel colour camera. Improved resolution could be found with a tri-CCD colour or gray scale camera. As image resolution was not a limiting factor in this application, a commercially available mono-ccd camera was selected.

Image distortion produced by cameras and lenses varies with the distance to the subject, distance from the centre of the image, and focal length setting. There are two main types of radial distortion: pincushion and barrel. Barrel distortion commonly occurs with wide-angle lenses when image points are displaced closer to the optical axis (negative displacement). Pincushion distortion occurs when points are displaced further from the optical axis (positive displacement) as shown in Figure 3.4. While distortions may not affect the quality of an image, they do affect image geometry which is of importance in this application.

![Barrel distortion](a) Pincushion distortion. (b)

Figure 3.4: Examples of radial distortion on image geometry.

Assessment of the distortion present in the system was performed according to the calibration method developed by Zhang (1999) using the camera model specified by Heikkilä & Silvén (1997) (Bouguet, 2005). Figure 3.5 indicates that the lens (1:2.8-5.0, equivalent to a 35-105mm zoom lens) was subject to barrel distortions on the outer edges. The location of the tennis ball during imaging is marked by the red circle in the centre of image. No corrections were made to the images as the ball was circular and located in the centre of the image.

Additional care was also paid to image focus, as an out of focus image will make it hard to clearly threshold the ball edges as in Figures 3.6(a) and 3.6(b). Figures 3.6(c) and 3.6(d) show an in-focus image that allows the ball fuzz to be easily separated from the background for accurate analysis. Image focus is important for algorithm implementation, as it can drastically alter the binary image presented for processing.

3.4.2 Lighting

Perhaps the most important factor in image capture is the lighting used in conjunction with the ball and camera set up. This influences not necessarily the illumination and capture of the ball centre, but those
of the ball edges and fuzz. Five different lighting set ups were examined and evaluated for their effects on image quality and the algorithm result. Example images and lighting setups are summarised in Table 3.1.

The ring lighting set up was most effective in providing the right intensity and positioning of light as the circular balance overcomes shadowing problems found in other methods. A range of ring lights were examined for their abilities to adequately highlight the edges of a range of tennis ball samples. There are many small diameter lights (5-8cm) available for use with microscopes, but it was found they struggled to provide enough light, at the right locations, to highlight the ball edges. Wider lights produce more light around the ball edges and minimise glare from the centre of the ball. The distance of the lighting from the ball will differ between individual setups based on light size and diameter as well as camera positioning. In this experimental setup, the light was 25cm in diameter and positioned 20cm above the ball (as shown in Figure 3.3).

### 3.4.3 Surface Conditioning

Surface roughness assessment is generally applied to rigid objects, such as metals with surfaces unaffected by use and handling like textiles. Over time and non-use, ball fuzz can become matted to the surface and make distinguishing differences between balls difficult, even when they possess observable differences. To address this problem, the surface of each ball was raised before processing.

Several methods of consistent and uniform surface processing were examined. The most successful method utilised a standard utility vacuum (1400W) with a 5cm hose. Several hose diameters and power levels were examined for their effects on ball roughness values, though no significant differences were observed. It should be noted that processing was confined to a single, uniform pass over the entire ball surface. Raising improved the range of differentiation between balls by 50%. Pre and post vacuuming surface characteristics are shown in Figure 3.7.
<table>
<thead>
<tr>
<th>Lighting method</th>
<th>Description</th>
<th>Image example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single light source</td>
<td>Highlights centre of ball, edges not clearly illuminated. Prone to shadows and uneven illumination.</td>
<td></td>
</tr>
<tr>
<td>Ambient natural lighting</td>
<td>Not enough contrast between ball and background. Threshold must be very low to separate ball from background, eliminating edge detail.</td>
<td></td>
</tr>
<tr>
<td>Balanced, bright light</td>
<td>Shadows on top and bottom of the ball. Lighting is too bright, making separation of ball from background difficult.</td>
<td></td>
</tr>
<tr>
<td>Camera flash</td>
<td>Uneven lighting on ball even when flash is centred above ball. It does not allow for global thresholding methods using image histogram data.</td>
<td></td>
</tr>
<tr>
<td>Ring lighting</td>
<td>Provides balanced lighting that eliminates shadows and highlights ball edges. Most successful method and allows for easy thresholding.</td>
<td></td>
</tr>
</tbody>
</table>
3.5 Image Pre-Processing

There are several steps required to successfully transform the captured colour image into a binary one that can be used in processing. This process was incorporated into MATLAB programming implemented using the graphical user interface (GUI) shown in Figure 3.17.

The initial image is cropped, reducing processing time and the chance of image noise outside the ball's effective area. The colour image is initially transformed to greyscale by taking a weighted sum of the red, green, and blue components to produce an 8-bit image with 256 shades of grey. This greyscale image is transformed to a binary image, where the edges are then selected. This image progression is shown in Figure 3.8.

Thresholding is important for consistent image processing and roughness results. The selected threshold must minimise image noise, such as that present in the lower left corner of Figure 3.9(a). As it is likely that at least some images will possess image noise, the GUI has been developed to allow the user to manually select a rectangular region to remove noise from the image.

3.5.1 Thresholding

The binary image is important to the accurate implementation of the roughness algorithm. While dependent on the physical set up and image capture, the thresholding of the greyscale image can be performed in many ways - producing very different final images (Gonzalez & Woods, 2001). Three types of image thresholding methods are discussed below.

Global The threshold relies only on the image grey levels. Ideally used for bimodal histograms with tall narrow peaks separated by deep valleys. High contrast images are characterised by pixel groupings at the white and black ends of the spectrum.
Local The threshold depends on the image grey levels along with another local property such as entropy, gradient, or neighbourhood averaging.

Adaptive The threshold is determined from the spatial coordinates of the image, along with other local or global characteristics. An example of this could be dividing a large image into subimages to adjust for uneven lighting.

For this application, a global method was desired as it depends only on image grey values and is particularly applicable to high contrast images. A thresholded image, $b(x,y)$, is determined according to equation 3.2, where $f(x,y)$ are grey levels from 0 to 255 and $Th$ is the threshold between these values.

$$b(x,y) = \begin{cases} 1 & \text{if } f(x,y) > Th \\ 0 & \text{if } f(x,y) \leq Th \end{cases}$$  

(3.2)

The image capture environment was optimised to create a bimodal histogram, with tall narrow peaks separated by deep valleys. Grey level global thresholding is the simplest method and effective in this application because of the shape and distribution of the image histogram. Varied thresholds are shown in Figure 3.9. The increase in image noise occurring with low thresholds is reflected in the large numbers of errant white pixels in Figure 3.9(a). While global thresholding methods, such as Otsu's (1979) algorithm, work well with bimodal histograms, it was found they consistently placed the threshold near the middle of the peaks. This level eliminated much of the detail on the ball surface and differences in roughness values. Figure 3.9(c) shows the reduced surface detail present with higher threshold values.

![Figure 3.9](image)

(a) Low threshold. (b) Optimal threshold. (c) High threshold.

Figure 3.9: Output images from a range of threshold values.

To reduce image noise, a new method was developed to place the threshold immediately after the first peak in the histogram. An example of threshold placement is shown in Figure 3.10(a). To do this, a normal distribution was fit to the data values in this peak, and the threshold placed three standard deviations above the mean, incorporating 99.7% of the histogram data. These results consistently produced images incorporating the desired amount of ball detail as shown in Figure 3.9(b). The location and effects of threshold placement on image noise and roughness values are shown in Figure 3.10(b). Image noise is noticeably reduced with increasing threshold values, improving processing consistency. In the region surrounding threshold placement, roughness values for image samples also remain relatively consistent.

3.6 Algorithm Implementation

Three methods of shape and roughness were considered in initial processing: fuzz density, sphericity, and roughness profile. The density method is shown in Figure 3.11, with the transformed ball surface and resulting column and row fuzz densities. Results from this method indicated inadequate differentiation between samples and limited emphasis placed on longer fuzz strands. The density method can also be very reliant on the number of background and ball pixels included in calculations.
Figure 3.10: Characteristics of threshold placement.

Figure 3.12(a) shows the implementation of the sphericity method with regards to an outlined ball profile. This method placed too much emphasis on longer fuzz strands protruding from the ball surface and did not incorporate any other surface detail. The final roughness measures required a flat ball profile similar to the one used in the density evaluation in Figure 3.11(a). The mean roughness depth ($R_z$) is the average of the distance between the five highest peaks and five lowest valleys. Mean profile deviation ($R_A$) is calculated as in Equation 3.3.

$$R_A = \frac{1}{L} \int_0^L |y(x)| \, dx \approx \frac{1}{L} \sum_{0}^{L} |y(x)|$$  \hspace{1cm} (3.3)

It was again found that the $R_z$ value placed too much emphasis on profile peaks, making it unsuitable for comparison to performance and perception data that is not dominated by a few long strands of fuzz. The $R_A$ roughness values provided a good range of differentiation between samples and showed promising results. Subsequent efforts were directed towards optimising this method. For the remainder of this thesis, the DFM and roughness results refer to calculations performed according to Equation 3.3.

For the $R_A$ method, a surface profile was calculated for each ball image by generating a vector of radial distances from an outlined, binary image like the one in Figure 3.12(d). These radial distances were fitted with a least squares, zero degree polynomial (horizontal line) and the absolute differences between the profile and this line were then averaged over the ball circumference to produce the $R_A$ value in pixels. To convert to a known distance, a calibration image was used to produce a length-to-pixel ratio as previously discussed.

### 3.6.1 Determining Ball Centre

There are several methods commonly used in standard metrology to determine an object’s centre point. These include a least squares circle (LS), a minimum circumscribed circle (MCC), and a maximum inscribed circle (MIC) (BSI, 1987). A minimum zone circle (MZ) method was also investigated which selects a centre point by minimising the distance between the minimum and maximum radii. Many image processing programs use a centre of mass (CM) calculation to produce a centre point, so this method was investigated as it was the only one that used the ball area in calculations. Other methods rely only on the ball outline, presenting difficulties similar to those observed with the sphericity method.

The MCC, MIC, and MZ circles are calculated using a Voronoi diagram for all edge points of the ball shape. A Voronoi diagram is a partition of space where each region corresponds to a point of the set (Feng & Hopp, 1991). The LS fit determines the centre point and radius of a circle by minimising the sum of the squares of the offset points in the ball’s edges. The CM calculation averaged the locations of all points...
Figure 3.11: Application of fuzz density method developed by Hsi et al. (2000).

Figure 3.12: Sphericity and roughness algorithm implementation.
in the ball's frontal area, shown in Figure 3.8(c), to produce centre coordinates. Morphological filters, including erosion and dilation, were used on the binary ball image to prevent uneven fuzz distributions on the ball surface from disproportionately affecting CM calculations.

Each of these methods produced a unique centre point. Results for a sample image are shown in Figure 3.13, with points differing by as much as 50 pixels. When unsuitable centre points were used to construct a roughness profile, results indicated a noticeable low frequency component. Filters can be used to remove waviness components from these profiles, as in Figure 3.14. These filters, however, also remove small out-of-roundness components, such as fuzz tufts on balls like the one in Figure 3.1(c), from roughness calculations. It was determined that filter use decreased differentiation between ball samples and that by optimising the ball's centre point, filter use could be avoided. The centroid method created the most suitable ball profile for analysis as indicated by Figure 3.15(b).

3.6.2 Generating a Roughness Profile

Using a centre point for each ball image, ball edges were converted to polar pixel locations with radial and angular components. These values were calculated to the nearest hundredth of a pixel. The transformation process for an image is shown in Figure 3.15. The accurate centre point is demonstrated by the flatness of the transformed ball image in Figure 3.15(b).

3.7 Important Considerations

This section addresses areas important to the overall success of the metric not addressed during development. These areas include ball seams and outlying strands of fuzz, the number of images used to characterise a single ball, and the consistency of application and results.

3.7.1 Role of Seams and Outliers

One of the biggest advantages of the $R_A$ roughness method when compared to other methods investigated, is that it is less susceptible to seams and outliers (long, protruding pieces of fuzz) in the ball's surface. Figures 3.16(a) and 3.16(b) show that an outlier has a noticeable effect on the roughness value for a given image (17% change). Ball seams are more noticeable on balder balls (as the fuzz doesn't cover them up), but had a smaller effect on the roughness results (1%, Figures 3.16(c) and 3.16(d)). Because multiple images will be used to characterise a single ball, the effects of seams and outliers will be averaged with other sample images. Balls with outliers produce higher average roughness values, with larger standard deviations. This increase is expected to correlate with player perceptions of ball condition as the outliers will be noticed by players. Larger standard deviations in measurements can also be used to characterise balls with loose fuzz, as opposed to those with tufted fuzz. Examples of these fuzz types are shown in Figure 3.1.

3.7.2 Determination of Sample Size

No one image will completely characterise the surface of a tennis ball, as it is a three-dimensional object being assessed with a two-dimensional method. It is unknown, however, how many images are required to produce results representative of the entire ball. By taking images of different random ball orientations, values can be averaged to reflect overall ball condition. The number of images must be a compromise between thoroughness and efficiency as more images may better characterise the ball's condition, but will be time consuming and require increased digital storage.

For a normal distribution, a confidence interval around the sample mean can be established through the calculation shown in Equation 3.4. Error was calculated at the $\alpha = 0.05$ significance level for the previously identified four fuzz types.
Figure 3.13: Diagram of circles used to determine centre points.

Figure 3.14: Example of filter use on an image with an inaccurate centre point.

Figure 3.15: Transform of a binary image into a roughness profile.
Figure 3.16: Role of seams and outliers in roughness results.

\[ E = t_{\alpha/2,DOF-2} \frac{\sigma}{\sqrt{n}} \] (3.4)

Four balls types, identified according to stages of textile wear and shown in Figure 3.1, were used in the determination of sample sizes. Table 3.2 shows the required sample sizes for a population of 120 images for each ball type. The results produced a large range of required sample sizes, depending on the desired level of accuracy and the variation in the ball samples. The table indicates that new and bald balls can be characterised with only a few images, but that the fuzzy samples require larger numbers due to surface variations. With regards to digital storage limitations for the desired image resolution and processing time considerations, 12 images was selected as an acceptable number of images for each ball sample. This will provide, at worst, 83μm of error using the \( R_A \) roughness method.

<table>
<thead>
<tr>
<th>Error value (μm)</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>New</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Loose fuzz</td>
<td>18</td>
<td>12</td>
<td>9</td>
<td>7</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Tufted fuzz</td>
<td>31</td>
<td>22</td>
<td>16</td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

3.7.3 Consistency

The DFM is designed to eliminate as much human intervention as possible by using automatic processing features. There are two areas to consider with regards to consistency:

Image consistency The same image must produce the same results each time it is processed.

Experimental consistency The same ball must produce the same or similar results when photographed with new setups.
Image Consistency

Although automatic thresholding produces a consistent binary image, occasional user intervention is required to monitor image noise. Morphological filters, such as erosion and dilation, were avoided as they demonstrated the potential to have significant effects on the ball image.

Table 3.3 shows the results of repeated processing of sample images for four general ball types in differing stages of wear. All images produced values with standard deviations of less than two percent of their respective roughness values. The new and slightly fuzzy balls had the highest variations, likely because of the long strings of fuzz protruding from the ball surface that can produce inconsistently processed image noise. The biggest variations were found when the cropped image area differed noticeably for a given image, potentially introducing unexpected image noise. Images produced the same threshold during each iteration.

Experimental Consistency

A ball must also produce consistent roughness values during repeated testing. Table 3.3 shows the results from experimental variations when each ball was evaluated in ten separate testing setups. The standard deviations are noticeably higher, with variations as large as 11% of the average ball roughness. It is understandable that there is slightly more variation in this process than individual image processing. These variations still allow the metric to operate at an adequate accuracy level which will be discussed in the following section. Table 3.3 also shows the increased variation present with fuzzier samples due to increased surface irregularities as compared to the new and bald samples.

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Image RA (mm)</th>
<th>Experimental RA (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald</td>
<td>2.519 ± 0.0010</td>
<td>2.723 ± 0.2061</td>
</tr>
<tr>
<td>New</td>
<td>4.130 ± 0.0209</td>
<td>4.401 ± 0.4159</td>
</tr>
<tr>
<td>Loose fuzz</td>
<td>5.701 ± 0.0363</td>
<td>5.930 ± 0.6424</td>
</tr>
<tr>
<td>Tufted fuzz</td>
<td>5.517 ± 0.0055</td>
<td>5.714 ± 0.6458</td>
</tr>
</tbody>
</table>

3.7.4 Automation of Process

A major advantage in developing the algorithm within the MATLAB programming environment is the range of processing capabilities available. MATLAB stores images as two-dimensional arrays, with the image pixels represented as matrix elements. This storage format allows for systematic access and data processing. In addition to standard processing capabilities, MATLAB has functions as part of the Image Processing Toolbox that perform spatial transformations, filtering, morphological operations, image enhancement, and regional processing. These specialised functions are comparable to those found in many commercially available image processing programs such as Image Pro Plus, Corel Draw, and Paint Shop Pro.

The MATLAB GUIDE (graphical user interface development environment) system facilitates the layout of features such as axes, buttons, panels, and text fields while creating a code file to allow manual insertion of specific callback operations. With a successful program running in the MATLAB environment, MATLAB can use a compiler such as Microsoft Visual C/C++ to generate stand alone programs for deployment on other machines and use in a non-MATLAB environment. An example of the finished GUI is shown in Figure 3.17. A user guide is provided in Appendix A with full coding is listed in Appendix B.

3.8 Error Analysis

There are three areas of error to consider when analysing the overall accuracy of this metric: human, systematic, and random.
Human Mistakes due to human involvement not generally included in error analysis. Minimised through appropriate training.

Systematic Inherent errors due to the experimental setup. They can be difficult to detect and statistical analysis is not generally useful.

Random Error naturally occurring through limitations of the measurement. Can be minimised through repeated measurements.

As this is a new method of roughness assessment, it is difficult to determine systematic errors that may contribute to inaccurate results. Any systematic errors that are present would likely exist in the surface transformation and creation of the roughness profile.

Three major sources of random error were identified during the development and optimisation of the fuzziness metric: calibration, image, and experimental. Random error can be minimised through improving data collection and repeating measurements. To compute the overall accuracy of the metric, each source of error must be considered. Image error will be accounted for using the standard error of the mean, which incorporates the deviation in each sample contributing to the mean value of the 12 images and is shown in Equation 3.5. The propagation of experimental and calibration error will be analysed using the sum and product error combination methods shown, respectively, in Equations 3.6 and 3.7.

\[
\sigma_X = \frac{\sigma_x}{n^{\frac{1}{2}}}
\]

\[
\sigma_X = \left[ \sigma_{x_1}^2 + \sigma_{x_2}^2 \right]^{\frac{1}{2}}
\]

\[
\frac{\sigma_X}{X} = \left[ \frac{\sigma_{x_1}^2}{x_1} + \frac{\sigma_{x_2}^2}{x_2} \right]^{\frac{1}{2}}
\]
Using the standard deviations computed in the previous sections, the overall standard deviation on the metric is determined to be 87\(\mu\)m using the \(R_A\) roughness calculation. This is acceptable as an error measure as it still allows differentiation between the ball samples. Human error was not considered as the application has not yet been deployed to outside users. It is expected that with wider use of the method, an analysis of human error will be required.

### 3.9 Summary

A digital fuzziness metric has been developed to objectively characterise the surface condition of tennis balls. This method allows the condition of tennis balls to be objectively assessed to an accuracy of ±87\(\mu\)m using an applied \(R_A\) roughness algorithm.

The DFM indicates good image and experimental consistency, with the ability to characterise ball surfaces independently of physical ball size. The relative simplicity of the application also indicates the practicality of the metric and its ability to be used in a variety of environments. The relationship with ball performance and player perception data will be more thoroughly discussed in the following chapter, detailing metric validation. Throughout this thesis, ball roughness values will refer to \(R_A\) values calculated using the DFM.

Additionally, several key areas have been identified for consideration in a range of alternate implementations. These include camera specifications, lighting, image thresholding, and methods to generate a surface roughness profile for analysis. Methods of examining algorithm consistency and error have also been detailed.
Chapter 4

Metric Validation

Chapter 3 describes the development of a digital fuzziness metric to assess tennis ball surface condition. This metric was devised to objectively relate ball surface condition to ball performance and perceived fuzziness. This chapter describes two investigations used to validate metric measurements. Performance data was gathered from wind tunnel tests and drag force measurements indicative of flight differences in the balls. A second sensory evaluation study determined perceived fuzziness levels for a range of ball samples. Data was directly compared to metric roughness values calculated for ball samples to evaluate the relevance of the DFM to performance and perception data.

4.1 Performance

Recent aerodynamic work has indicated that fuzziness affects a ball’s drag coefficient (Cooke, 2000; Goodwill & Haake, 2004a; Mehta & Pallis, 2001a). Previous studies have included naturally worn, artificially shaved, and manually raised balls tested at a range of wind speeds. Unfortunately, ball conditions and test results from other authors cannot be compared as they provide only qualitative descriptions of ball condition. Testing performed in this section correlates drag coefficients of non-spinning tennis balls with metric roughness values. While spinning measurements may provide data more representative of the modern game, magnitudes are dependent on ball spin rate and airspeed. Non-spinning measurements were deemed more suitable as they provide a single value for comparison with the metric.

4.1.1 Testing Methodology

Non-dimensional drag coefficients were selected to assess ball performance properties. They are determined from the shape and surface characteristics of an object. As net drag forces are dependent on ball size, they were not suitable for use as the metric was developed to be independent of this. Nine worn balls were tested in a wind tunnel through a range of wind speeds found in the modern game.

Tunnel Specifications

The tunnel available for use at Loughborough University possesses a large working section and less than 0.2% velocity variation at the working section midpoint. Samples were mounted above the boundary layer associated with the edge of the tunnel to ensure steady airflow during testing. Data was calculated from 100 samples averaged over a 20 second interval for speeds from 0-45ms⁻¹. Full tunnel specifications are detailed in Section 7.1.1.

Balls were supported from a sting connected to the force balance mounted below the tunnel, shown in Figure 4.1. This support method looked to minimise interference by securing the sting in the wake of the ball (Chadwick & Haake, 2000b; Sayers, 2003). All balls were mounted in the same orientation with the ball logo centred on the forward-facing panel. Calibration data was taken for the sting over a range
of wind speeds and subtracted from the combined ball and sting measurements to determine ball drag coefficients. This process is discussed in further detail in Section 7.2.

**Ball Specifications**

Nine balls were selected to incorporate a range of ball conditions resulting from play. Further ball details are located in Table 7.1. Three new balls, two balls with loose fuzz in the early stages of wear, two tufted fuzz balls, and two bald balls were tested. Worn balls were collected from local courts and manufacturer returns to represent a range of ball conditions. All balls had a sateen weave covering. Images for the fuzziness metric were taken before testing as it was expected that testing could alter initial ball fuzziness levels.

**4.1.2 Results**

The drag coefficient for a tennis ball is partially dependent on the wind speed used during testing. As discussed in Chapter 2, a critical drop in the drag coefficient occurs during the airflow transition from the subcritical regime to the supercritical regime. After this transition, the drag coefficient begins to stabilise at higher wind speeds. The variation in drag coefficient for a typical ball is shown in Figure 4.2. To determine the value to use in metric comparison, an average was taken for values from 30-45ms\(^{-1}\), as the values remain relatively constant. Figure 4.3 shows the weak linear relationship between the drag coefficient and metric roughness values for the balls. This poor fit was not acceptable and another relationship examined.

Chapters 2 and 3 discuss cloth conditions occurring with wear in tennis balls. A new ball will initially fuzz up, producing long stringy fuzzy protruding from the ball. These fibres will then entangle to produce a tufted fuzz surface. Both types of fuzziness show increased drag as compared to a new ball, despite the differences in metric roughness. As pills and fibres are pulled from the tufted balls, they become increasingly bald with lower metric values and lower drag coefficients. The ball’s wearing process was incorporated using a least-squares ellipse fit to the metric and drag data. Figure 4.4 shows this relationship with an ellipse centred at \((0.527, 4.254)\), along with ball fuzz conditions. Performance implications of the wearing process are well represented by the ellipse fit with the data. The residuals are also randomly distributed, indicating good model fit.

**4.2 Perception**

Although the previous section shows the metric can indicate ball flight characteristics, player perception of ball condition is also considered important. Interviews conducted with elite players illustrate the role of ball fuzziness in determining predicted play characteristics (Loughborough University Tennis Team, 2004). Perceived ball fuzziness affects perceived performance properties and player attitudes towards ball condition and appearance. A sensory evaluation study was designed to relate player perception of ball fuzziness to metric values.
Three options were deemed suitable for gathering perception data on ball fuzziness. These included tactile evaluations, a postal survey with colour images, and an online survey. While tactile evaluations provide the most realistic viewing conditions for participants, only a relatively small sample population could be obtained in this manner. Solicitation of subjects at tournaments and club events would likely produce a high response rate at each event, but would limit evaluations to a small geographical area or specific talent level. As only a visual analysis of ball condition was required, postal and online surveys were developed as testing possibilities. Ball samples were largely uniform with regards to colouring and markings, with differences limited to fuzziness. Pilot testing indicated that representative, high-quality images captured ball detail and allowed for suitable sensory evaluation by panellists.

Continued improvements in technology have caused noticeable changes in how surveys are administered. Email surveys emerged in the 1980’s with web based surveys following in the 1990’s. A discussion of the
Table 4.1: Summary of advantages and disadvantages of postal surveys.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large sample</td>
<td>Length of time required for responses</td>
</tr>
<tr>
<td>No technological bias</td>
<td>Unclear instructions</td>
</tr>
<tr>
<td></td>
<td>Partial completion</td>
</tr>
<tr>
<td></td>
<td>Low response rate</td>
</tr>
<tr>
<td></td>
<td>Inability to control order of presentation</td>
</tr>
<tr>
<td></td>
<td>High cost</td>
</tr>
<tr>
<td></td>
<td>Perception as junk mail, impersonal</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of advantages and disadvantages of online survey techniques.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced response time</td>
<td>Perception as ‘junk mail’</td>
</tr>
<tr>
<td>Lowered costs</td>
<td>Skewed characteristics of internet population</td>
</tr>
<tr>
<td>Ease of data entry</td>
<td>Impersonal</td>
</tr>
<tr>
<td>Required completion of questions</td>
<td>Low response rate</td>
</tr>
<tr>
<td>Flexibility in format</td>
<td>Unclear instructions</td>
</tr>
<tr>
<td>Large sample easy to obtain</td>
<td>Technological variations</td>
</tr>
<tr>
<td>Ease of follow up</td>
<td></td>
</tr>
</tbody>
</table>

relative advantages and disadvantages of online and mailed surveys is shown in Tables 4.1 and 4.2 (Evans & Mathur, 2005; Granello & Wheaton, 2004; Klassen & Jacobs, 2001). One of the advantages in using mailed surveys over an online version is the lack of technological bias in the sample population. Scholl et al. (2002) suggest, however, that when most of a society has internet access, the lack of representativeness of the sample is no longer a drawback for use. The target population of university players and coaches was deemed to have suitable internet access, so an online technique was pursued. Steps taken to address limitations of this method are discussed throughout this section.

4.2.1 Online Survey Development

Individual pages were constructed using Macromedia Dreamweaver, a standard web page construction tool, and further functionality was added using three different web based languages.

**Hypertext Markup Language** (HTML) A platform independent markup language used in the creation of web pages. HTML is used to structure information, such as text and images, on web pages.

**Hypertext Preprocessor** (PHP) A general-purpose open source serve side scripting language that can be embedded into HTML to create dynamic content and interact with databases. It can create web based software applications.

**JavaScript** A open scripting language sharing many features with the full Java language. It can be used to develop interactive sites, create dynamic content, respond to user actions (button clicks), and validate data.

Ranking and rating are the two main techniques used to gather data from participants during sensory evaluations. Rating provides interval and ratio data that can be analysed using both parametric and non-parametric tests, though this is highly dependent on the sensitivity of the scaling system. With the use of an online system, it is also difficult to determine scale levels at which panellists associate ball fuzziness as each panellist could rate the balls differently. Ranking, however, requires little panel training and samples are placed in order of intensity. As player perception of absolute fuzziness levels will vary, rank methods are seen as the most useful technique in this application. Panellists are also generally familiar with this technique, making survey completion instructions more recognisable.
Block Design

Complete and partial block testing methods developed as a method to reduce the number of comparisons normally required from panelists during paired comparison designs, a popular technique of evaluating subtle sensory differences. Using object pairs, however, the evaluation of \( t \) objects requires \( \frac{t(t-1)}{2} \) comparisons from each panelist. While unbalanced paired comparison designs, where panelists investigate only a portion of the pairings, do exist - larger block sizes allow for more replications of the entire experiment and stronger conclusions to be formed (David, 1988).

The simplest block design involves all treatments presented in a random order for simultaneous consideration and ranking. The number of balls in this study prevented all the images from fitting on a standard computer screen. This would make it difficult for panelists to consider all treatments when ranking balls. A balanced partial block design presents a subset of these treatments to panelists for consideration, such that each pair of treatments appears together equally often (Dey, 1986). For sixteen balls \((t = 16)\), a block size of \( k = 4 \) creates five experimental replications, each containing four blocks. The design, shown in Table 4.3 was taken from a balanced lattice square design developed by Cochran & Cox (1957).

<table>
<thead>
<tr>
<th>Repetition I</th>
<th>Repetition II</th>
<th>Repetition III</th>
<th>Repetition IV</th>
<th>Repetition V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4</td>
<td>1 5 9 13</td>
<td>1 6 11 16</td>
<td>1 14 7 12</td>
<td>1 10 15 8</td>
</tr>
<tr>
<td>5 6 7 8</td>
<td>2 6 10 14</td>
<td>5 2 15 12</td>
<td>13 2 11 8</td>
<td>9 2 7 16</td>
</tr>
<tr>
<td>9 10 11 12</td>
<td>3 7 11 15</td>
<td>9 14 3 8</td>
<td>5 10 3 16</td>
<td>13 6 3 12</td>
</tr>
<tr>
<td>14 15 16</td>
<td>4 8 12 16</td>
<td>13 10 7 4</td>
<td>9 6 15 4</td>
<td>5 14 11 4</td>
</tr>
</tbody>
</table>

One repetition involved four block evaluations, each developed as an individual web page. Initial pilot testing suggested participants could complete eight blocks in an average time of 3.5 minutes. Although further pages could be incorporated into the design, it was felt that increased length may cause some participants to become uninterested in accurately ranking the balls, leading to survey abandonment and apathetic rankings. Deutsksens et al. (2004) find shorter questionnaires lead to significantly higher response rates and improved response quality.

The eight block combination can be formed from any of ten combinations of two of the five repetitions. One of these combinations was randomly selected for each panelist based on a random number generator (seeded with participant access time to prevent repeatable seeding). Once a grouping of eight pages was known, these eight pages were shuffled to produce a random order for presentation. To minimise complexity in survey coding and loading time, the four balls in each block were randomly assigned a fixed position in the blocking square shown in Figure 4.5. This minimised any order effects that could be associated with a linear vertical or horizontal arrangement.

Image and Ball Selection

Representative images were taken using a 5 mega-pixel camera. Particular attention was paid to lighting, colour, and logo differences in the samples, as fuzziness was the only ball attribute under investigation. Lighting used in the metric images is inappropriate for subjective ball differentiation as it does not present familiar ball images to players. Images were taken under ambient lighting conditions on a matte black background and cropped to the same size.

A range of samples was desired to determine perceptible levels of fuzziness by players. Sixteen images were selected from worn tennis balls evaluated in Chapter 8 by sensory analysis. Two of these images showed the ball logo to investigate the role it could play in fuzziness determination. All other images showed unmarked faces of the ball, with two of these images being unmarked examples of the logoed balls. Colour was controlled as much as possible when selecting the samples, though slight variations did occur as the balls were of differing manufacture and had sustained wear. Blocking configurations are shown in Appendix D.
Participant Selection

The survey was emailed to 190 coaches at American universities supporting male and female varsity tennis programs. Coaches were asked to complete the survey themselves, and then to forward it to their athletes (averaging ten to twenty players per coach, with a potential survey population of over 2000 respondents). The universities represented a range of school sizes and talent levels. This population of tennis players and coaches were selected because they train five to six days a week, giving them good familiarity with ball conditions. Universities are also generally known for good internet and email access.

Limitations

Four major limitations were identified in survey implementation and addressed before distribution.

- Impersonal and interpretation of survey as ‘junkmail’.
- Low response rate.
- Unclear instructions.
- Technological variations.

As all communication with panellists was performed via text, the survey could be seen as impersonal. There was also the perception that the survey could be ‘spam’ and responding may create further unwanted email. To address these problems, contact information was provided both in the email and on the starting page for the survey. Links to the University and Sports Technology Research Group were also provided to support the academic nature of the work. Emails were personally addressed to the coaches and participants were encouraged to reply with questions or comments concerning the research. Only background playing information was asked of panellists and no contact information was collected.

Incentives in online surveys have been shown to improve panellist response rates (Deutskens et al., 2004). For this investigation, however, monetary or product related incentives were not used as they
would have required contact information from panellists. It was felt that the response rate could be
similarly improved by not requiring contact email addresses from respondents, so this method was used.

Clear instructions were listed at several stages throughout the survey to minimise confusion. While
instructions on the first page of the survey indicated that the four balls on each page should be ranked from
1 for fuzzy samples to 4 for bald samples, no example rankings were given as these may have influenced
player perceptions of what a 'fuzzy' tennis ball looked like. Ranking values were repeated on each page to
remind panellists of the ball ordering. Drop down menus were also located beneath each sample indicating
the four rank values.

Two methods were implemented to monitor user responses during the survey. One function monitored
ball rankings on each page and prevented a user from assigning tied ranks to balls. If a ball received a
rank already used in a given block, the menu was reset and an alert window informed the panellist that
no tied ranks were allowed. If a panellist attempted to navigate to the next screen without ranking all of
the samples, the second function triggered another alert window reminding the user that all ball samples
required a rank value.

Pilot testing distributed the survey to users with a range of operating systems, web browsers, computer
screens, and computer processing speeds. Feedback contributed to increased image compression to improve
use with slower internet connections. While there existed variations in display brightness levels, viewing
conditions would affect each of the images in the same manner so was not deemed to play a significant
role in altering panellist rankings.

4.2.2 Results

Seventy-one survey responses were received over a one month period. Panellists averaged 16.7 years playing
experience and all played tennis on a daily or weekly basis. Table 4.4 indicates the percentage of panellists
assigned to each repetition of the design. Repetition IV is noticeably lower than the other four, but it
is expected that with higher numbers of respondents, the values would tend towards the 40% expected
with randomisation. Because of the balanced nature of the design, all balls were still evaluated the same
number of times, though each pairing was not.

<table>
<thead>
<tr>
<th>Repetition</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>43.7</td>
</tr>
<tr>
<td>II</td>
<td>39.4</td>
</tr>
<tr>
<td>III</td>
<td>42.3</td>
</tr>
<tr>
<td>IV</td>
<td>31.0</td>
</tr>
<tr>
<td>V</td>
<td>43.7</td>
</tr>
</tbody>
</table>

While measures of subject inconsistency, such as Kendall's coefficient of consistence, can be used in
complete paired comparison designs, the partial block nature of this design prevented panellists from being
removed due to inconsistent responses. Instead, pooled data was examined for significance as responses
were not analysed individually. Significance in rankings was determined using a method developed by
Durbin (1951) to determine agreement between panellists. The coefficient of concordance ($W$) is given in
Equation 4.1, where $SS$ is the sum of squared deviations from the mean, $n$ is the number of objects, and
$\lambda$ is the number of times a ball pairing is evaluated together in the design.

$$W = \frac{12SS}{\lambda^2n(n^2-1)} \quad (4.1)$$

Concordance within rankings indicates $W = 0.994$, which is above the critical value determined from
the F-distribution ($\alpha = 0.05$) of $W = 0.248$. Figure 4.6 shows the average ranks, plotted with one standard
error, for each of the blocks used. Lower ranks indicate fuzzier balls.
Figure 4.6: Average ranks for the blocks used in the survey. Ball numbers are listed above the data points.

Four of the blocks (1,4,11,13) indicated significant differences between the average ranks assigned to each ball, indicating that there was good agreement with these samples. Three of these included ball 16. Nine of the blocks (3,5,8,9,12,15,16,19,20) had two balls indicating significant differences, with the remaining two samples statistically similar. Only one block (2) showed a large overlap between balls. There were no significant differences in the standard errors associated with the fuzziest or baldest in each block - suggesting all ball conditions showed similar variations in user response.

Gulliksen & Tucker (1951) detail a procedure for determining paired comparison data from partial blocks and rank orders evaluated during testing. Each block of four balls contained six indirect paired comparisons and these comparisons were used to form a preference matrix for the data (Kendall & Babington Smith, 1940). As the analysis used examines the distribution of responses for a given ball pairing, the small differences in pairing evaluations did not affect the evaluation of results.

The paired comparison data was fit with a Bradley-Terry model as described in Section 9.5. The Bradley-Terry model is a probabilistic choice model that determines ratio scale measurements from the binary data produced from paired comparisons evaluations. These ratio measures can then be directly compared with directly measured characteristics such as ball fuzziness (Zimmer et al., 2004). An evaluation of the $\chi^2$ value for the fit can be used to evaluate the appropriateness of the Bradley-Terry model to the data (Wickelmaier & Schmid, 2004). The $\chi^2$ value indicates a poor probability that the model accounts for all the data ($p < 0.10$). A significance of $\alpha = 0.10$ is suggested to increase the chance of detecting violations of the model (Wickelmaier & Schmid, 2004). The Pearson correlation between the preference matrix and that predicted by the model, however, indicates strong agreement ($r = 0.931$). As the Pearson correlation was deemed an acceptable assessment of model fit by Davies (2005), further analysis of the data was pursued. It should be noted that parametric statistics were used in the analysis of the Bradely-Terry merit values as the model produced ratio data from the original ordinal data.
Figure 4.7 shows the relationship between the Bradley-Terry merit values for the 14 unmarked balls used in the survey and the fuzziness metric. Confidence intervals (95%) are plotted for both metric and merit values. The correlation indicates good agreement between the metric and panellist perceptions, though it is believed that the differences in fuzzy balls, ranging from loose to tufted, is the main source of variation. Some players may perceive a ball with longer, looser fuzz to be fuzzier than a ball with tufted fuzz, and vice versa. Even with these player differences in evaluating fuzz, the metric indicates good agreement with player perception of ball fuzziness. The random distribution of the residuals suggests a good fit of the linear model with the data.

Two logoed balls were included to examine any effects logo condition may have had on player rankings. One of the samples was a new ball while the other was a balding ball with a faded logo. Survey images were taken on opposite sides of the balls, so the fuzz profiles should have been similar. There was no difference in the perceived fuzziness of the bald balls, but the new ball with a logo was perceived to be significantly less fuzzy than its unmarked counterpart. While ball aesthetics will be further explored in Chapter 8, this initial investigation suggests the importance of the ball logo in player perception of ball fuzziness.

4.2.3 Comparison with Tactile Analysis

A limitation in using the online survey method is that participants evaluated only one image of each ball sample. This image attempted to reflect the ball’s representative fuzziness, though twelve images are used to calculate the metric value. In a tactile analysis, players would be free to handle and manipulate the balls, leading to an evaluation of the entire ball. To examine these limitations, comparisons were made with tactile evaluations discussed in detail in Section 8.2.2. Seven of the samples in the online survey were unmarked, pressureless balls differing only in surface condition. The comparison was limited to these samples as other tactile evaluations also included pressure, colour, and logo differences that were seen to affect player perceptions of ball condition.

Each set of data was fit with a linear best-fit line comparing ball rankings and metric roughness values. From these fits, 'perceived fuzziness' values could be determined from the rank values. Pearson’s correlation coefficient is 0.927 for the two perceived values, above the 0.874 critical value ($\alpha = 0.01$) given by Pearson’s table. These results indicate significant agreement between the online and tactile perception evaluations of ball fuzziness.

Figure 4.8 shows the relationship for these perceived fuzziness values. Given that the respective initial correlations for the online and tactile analyses were $R^2 = 0.840$ and $R^2 = 0.851$, this relationship shows
good agreement, though the online results tend to over-estimate the perceived fuzziness of the balder samples.

4.3 Concluding Comments

Steps taken to validate the fuzziness metric developed in Chapter 3 indicate good agreement with both ball performance and player perception data. The relationship between ball drag coefficients and metric data indicates that performance information can be determined from ball sample metric values. It should be noted, however, that the ball cloth must also be classified in one of four stages of wear to accurately predict the drag coefficient.

The development of an online sensory evaluation study indicated agreement between metric values and perceived ball fuzziness using rank evaluation methods. While there is variation due to differences in player perception and experience with fuzzy tennis balls, results still provide an acceptable level of agreement. This online survey also demonstrated a significant positive relationship with tactile evaluations performed by players, indicating its usefulness in assessing perceptible aesthetic differences.
Chapter 5

Causes of Ball Degradation

This chapter investigates potential causes of ball degradation, including both the effects of play and naturally occurring conditions. Flight, court interactions, and racket impacts, were identified as potential factors in ball deterioration and investigated for their effects on ball condition. Precipitation, natural pressure loss, and differences in ball construction were classified as naturally occurring considerations unrelated to play. Several measures of wear and degradation were used to monitor ball condition during testing. These included mass, fuzziness, internal pressure, and standardised test results. Results will be used to determine important areas for future work in dynamic impact, flight, and player perception testing.

5.1 Methods of Ball Wear

While footballs submitted for FIFA approval must meet water absorption (10-15% of ball’s mass) and size and shape retention requirements, there exist no specified durability tests or methods for tennis balls. After 2000 impacts FIFA approved balls are limited to a maximum increase in circumference of 1.5cm, a maximum deviation in sphericity of 1.5%, and less than 10kPa change in pressure (FIFA, 1998). Stages of tennis ball wear would ideally be observed during play on a variety of court surfaces, incorporating a range of racket characteristics and playing speeds. Relying on players, however, creates additional variables that will affect wearing and produce unrepeatable results. Player involvement was also impractical as over 35,000 impacts were desired for a thorough investigation. Several alternative methods were developed to simulate wear and degradation in ball samples. Mitchell et al. (2001) calculate that approximately 30 shots are played per game, averaging 45 impacts per ball over nine games. Impact levels of 50 and 100 impacts were selected for use during testing to encompass elite match play, though 250 and 500 impacts were also determined appropriate for the more substantiated wear found in balls used by recreational players.

With the variety of factors involved in testing, no single method was deemed suitable for wearing. Miller & Messner (2003) and Capel-Davies & Miller (2003) use a ‘wear tester’ to fire balls at 20ms⁻¹ with an inbound angle of 15° at a rough acrylic surface. A pneumatic Lobster ball machine has also been used to fire balls at 800, 1600, 2400, 3200, and 4000 impacts into a hard surface (Rand et al., 1979). Two similar methods were utilised in testing performed in this chapter.

Pneumatic Air Cannon A pressurised air cannon fired balls at a rigidly clamped racket head. This setup allowed testing to focus on the effects of racket differences on ball wear. During testing each ball was manually placed into the cannon and collected from the impact chamber. This made testing both labour and time intensive, suggesting a need for alternative methods.

Automated Racket Impact System Differences in ball construction and precipitation were evaluated using an automated racket impact system at the Milliken Woollen Speciality Products production facility. This system allowed large numbers of impacts to be performed automatically, with a timed control system. While the impact count was slightly less accurate than the manual method, the
improvements in efficiency and ease of implementation were seen as important benefits. Balls were dropped from a hanging collection bin and impacted with a racket head speed of approximately 15ms\(^{-1}\). The balls impacted two angled surfaces before being returned to the bin. The hit rate averaged 33.9 impacts per minute (\(\sigma = 1.76\)), leading to differences in impact levels of 2-3 impacts per 50.

Standard deviations for mass and fuzz measurements on each type of ball, at each impact level, were used to monitor the consistency of these wearing methods. Table 5.1 indicates the automated racket system showed more variability than the manual method using the air cannon. This can be explained by the small differences in the number of impacts received by each ball. There was no evidence for increased variability at higher impact levels (\(p = 0.394\)).

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Pneumatic Cannon</th>
<th>Racket Whacker</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (g)</td>
<td>Fuzz (mm)</td>
</tr>
<tr>
<td>50</td>
<td>0.067</td>
<td>0.020</td>
</tr>
<tr>
<td>100</td>
<td>0.119</td>
<td>0.035</td>
</tr>
<tr>
<td>250</td>
<td>0.086</td>
<td>0.024</td>
</tr>
<tr>
<td>500</td>
<td>0.123</td>
<td>0.069</td>
</tr>
</tbody>
</table>

Differences in ball wear due court surface differences were examined using balls from professional tournaments throughout Great Britain. Worn balls were gathered from three LTA professional tournaments and examined for mass and fuzziness differences.

5.2 Wear Caused Through Play

Wear is defined in this thesis as changes to ball characteristics caused through play. Figure 5.1 shows the approach used to assess important contributions to wear differences including racket impacts, court interactions, and changes from flight. Ball mass and fuzziness were used as wear indicators for all samples.

![Figure 5.1: Components of wear caused through play.](image)

5.2.1 Racket Factors

An investigation was developed to monitor wear rising from changes to the modern game. Factors included increased ball speed, higher stringing tensions, and the emergence of varied string types. As discussed in the previous section, an air cannon was used in all racket testing. Dunlop 200G racket heads were rigidly clamped at 45° for all testing. Research indicates improved differentiation between impact conditions with rigidly clamped racket heads as opposed to freely suspended rackets (Haake et al., 2000a). Impacts
were performed at 35 ms\(^{-1}\) as it approximates the speed of a 65 ms\(^{-1}\) serve as it reaches the opposing baseline (Pallis, 1999b). Two balls were monitored at each impact level and stringbed configuration. Balls were manually fired with an air cannon and collected in an impact chamber, for a total of 9000 impacts. Pressureless balls were used as testing was conducted over a five day period.

**String Type**

Three types of string commonly used by professional players were examined for their effects on ball characteristics. These three strings were chosen as a representative sample of professional players (USRSA, 2005). Properties of the strings are listed in Table 5.2. All strings were 1.30mm in diameter.

The synthetic and natural gut strings were strung at 27.3kg (60lb) tension, similar to tensions used by professional players. The polyester was strung at 24.5kg (54lb) in accordance with the 10\% lower stringing tension recommended by the manufacturer. Figure 5.2 shows that the natural gut demonstrates increased ball mass loss and higher initial fuzziness as compared to the synthetic gut. Polyester had the lowest rate of ball mass loss, though the highest fuzziness through 100 impacts.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gut</td>
<td>Babolat VS Team Superb elasticity, tension stability, and liveliness, though can lack durability and break easily.</td>
</tr>
<tr>
<td>Synthetic gut</td>
<td>Prince P9 synthetic gut Uses modern technology to play like natural gut, but with the advantage of increased durability.</td>
</tr>
<tr>
<td>Polyester</td>
<td>Luxilon Big Banger Single polyester fiber, with a thin coating (monofilament construction). Generally quite stiff and loses tension quickly, but possesses increased durability.</td>
</tr>
</tbody>
</table>

**Table 5.2: Strings used in racket impact testing.**

---

**Figure 5.2: Evaluation of string type on ball wear.**

**String Tension**

Elite players are known to use high stringing tensions, favouring increased control over the power found with lower tensioned strings (Brody et al., 2002). Two tensions were investigated, 22.7kg (50lb) and 27.3kg (60lb), to evaluate any differences in ball mass loss and fuzziness characteristics. Cottey (2002) uses these two values as upper and lower limits during an analysis of ball spin generation. Further extreme values were seen to be unsuitable regarding tensions generally used in the modern game (USRSA, 2005).
Figure 5.3(a) indicates that differences in string tension have no effect on ball mass loss, though the lower tension does produce higher fuzziness at 100 and 500 impacts. The longer contact times associated with lower string tensions could contribute to the increased fuzziness (Haake et al., 2003).

![Figure 5.3: Evaluation of string tension on ball wear.](image)

**Impact Speed**

A slower testing speed of 25ms⁻¹ was selected as an alternate testing speed to approximate volley impact conditions and the slower speeds used by lower level players. Figure 5.4(a) clearly demonstrates the increased mass loss with a higher impact speed. Figure 5.4(b) shows that after 100 impacts, the lower impact speed contributes to lower fuzziness values. With the large differences mass loss, ball speed is perhaps the most important of the three stringbed properties investigated.

![Figure 5.4: Evaluation of ball speed on ball wear.](image)

**Conclusions from Racket Wear Testing**

While testing indicated differences between stringbed properties in ball wear, there were limitations due to the labour intensive nature of testing. The number of balls at each level was restricted, as were the number of string tensions and impact speeds used. It is also unclear how these results will translate to physical play, with a range of shot types, ball speeds, and court surfaces.

All three investigations showed initial increases in fuzziness through 50-100 impacts, with declining values through 500 impacts. Impact speed produced the largest differences in ball mass loss, though
limited differences in fuzziness. This suggests that ball wear, with regards to mass loss, will differ greatly between recreational players and professionals. For elite players, however, stringing variations could create differences in ball wear during play.

Previous research has used mass loss as a measure of wear over repeated impacts. The relationship between mass loss and fuzziness is shown in Figure 5.5. The weak negative relationship between mass and fuzz changes to balls has implications to aerodynamic performance that relies both on ball mass and surface condition. These results also suggest that individual ball fuzziness cannot be predicted from mass loss, though a stronger relationship may exist for averaged results.

![Figure 5.5: Mass loss and ball fuzziness relationship during racket testing.](image)

### 5.2.2 Court Factors

Balls were collected from men’s and ladies’ acrylic court, clay, and grass professional tournaments. The number of games using each tube of balls was recorded, though the exact number of shots was not. Each tube of four balls was used for the specified number of games and then returned to its tin. Results are averaged for each tube of balls and all tournaments involved players of a similar professional standard. All balls were collected from singles matches.

**Acrylic court**

Forty tennis balls were gathered from play at an indoor acrylic court tournament utilising Slazenger Wimbledon balls. The ball change occurred at 11 and 13 games, though the ladies’ qualifying matches used balls for two sets before a ball change was made. Due to tournament constraints, original ball masses and roughness levels could not be documented. Post-play ball characteristics are shown in Table 5.3. It should be noted that the balls played with for 11 games and 2 sets also included play during match warm up.

Compared to new balls, the worn balls generally showed larger mass variation per tube of balls ($\sigma_{new} = 0.54$), though smaller roughness variations ($\sigma_{new} = 0.41$). More consistent fuzziness values can be attributed to the elimination of longer fibres removed from the new balls. Compared to a typical new ball, worn balls likely lost at least a gram of cloth during play. Average fuzziness for a new Slazenger Wimbledon ball was 4.40mm. There are no trends between ball roughness and mass, though individual ball losses were not able to be recorded.

Figure 5.6(a) does not indicate a relationship between ball mass and the number of games used, though it is expected individual ball mass loss data would give more conclusive results. Changes to ball fuzziness
Table 5.3: Characteristics of balls used during a acrylic court tournament.

<table>
<thead>
<tr>
<th></th>
<th>Ladies' Games</th>
<th>Mass (g)</th>
<th>Roughness (mm)</th>
<th>Gentlemen's Games</th>
<th>Mass (g)</th>
<th>Roughness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>56.61 (0.61)</td>
<td>3.39 (0.35)</td>
<td></td>
<td>4</td>
<td>56.15 (1.07)</td>
<td>3.72 (0.51)</td>
</tr>
<tr>
<td>17</td>
<td>56.42 (0.84)</td>
<td>3.28 (0.08)</td>
<td></td>
<td>5</td>
<td>55.87 (1.10)</td>
<td>3.82 (0.13)</td>
</tr>
<tr>
<td>18</td>
<td>56.30 (0.60)</td>
<td>3.07 (0.14)</td>
<td></td>
<td>11</td>
<td>56.78 (0.27)</td>
<td>3.17 (0.08)</td>
</tr>
<tr>
<td>19</td>
<td>56.44 (0.75)</td>
<td>3.39 (0.48)</td>
<td></td>
<td>11</td>
<td>56.70 (0.85)</td>
<td>3.17 (0.26)</td>
</tr>
<tr>
<td>25</td>
<td>56.16 (1.02)</td>
<td>3.19 (0.49)</td>
<td></td>
<td>11</td>
<td>56.42 (0.69)</td>
<td>3.39 (0.11)</td>
</tr>
</tbody>
</table>

Note: standard deviations given in parentheses.

(a) Ball Masses.  
(b) Fuzziness.

Figure 5.6: Evaluation of acrylic court ball wear.

are shown in Figure 5.6(b). None of the samples collected appear to show increased fuzziness as compared to a new ball, though this could occur in the initial few games for which no data was collected. The mens' results suggest a higher rate of roughness loss than the ladies, but as extended results are not available this hypothesis cannot be verified.

Clay

Thirty-two balls were collected from a professional tournament on a green clay surface using Slazenger Wimbledon balls. Seven tubes were collected from men's play after the ball change at 11 games, while one tube was collected from a ladies qualifying match using the balls for two sets (15 games). Play occurred in cool, dry conditions. All balls were also used during the pre-match warm up. Table 5.4 details ball mass and fuzziness measurements. A relationship between ball mass and fuzziness was not examined as balls were collected from similar numbers of games and did not provide a suitable range of characteristics. Any relationships in data would most likely be due to chance, rather than wearing characteristics of the surface.

The clay court samples generally show higher mass and fuzziness measurements as compared to the acrylic court samples. These results suggest that clay surfaces cause lower mass losses compared to an abrasive acrylic court surface that may shear cloth from the balls during impacts, similar to results previously recorded (ITF, 2006a). Higher ball fuzziness is also linked to the lower amounts of fuzz removed, but still raised, from the ball surfaces. All balls exhibited tufted fuzz. While the variation in the fuzziness measurements per tube of balls is similar to the acrylic court data, the masses generally show smaller variations. This is attributed to the higher ball masses, and lower losses, occurring with play on clay surfaces.
Table 5.4: Characteristics of balls used during a clay court tournament.

<table>
<thead>
<tr>
<th>Match</th>
<th>Mass (g)</th>
<th>Roughness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men's 1</td>
<td>57.24 (0.32)</td>
<td>3.65 (0.22)</td>
</tr>
<tr>
<td>Men's 2</td>
<td>57.40 (0.28)</td>
<td>3.55 (0.15)</td>
</tr>
<tr>
<td>Men's 3</td>
<td>57.65 (0.38)</td>
<td>3.37 (0.33)</td>
</tr>
<tr>
<td>Men's 4</td>
<td>57.05 (0.47)</td>
<td>3.71 (0.40)</td>
</tr>
<tr>
<td>Men's 5</td>
<td>58.13 (0.45)</td>
<td>3.42 (0.27)</td>
</tr>
<tr>
<td>Men's 6</td>
<td>57.33 (0.73)</td>
<td>4.07 (0.41)</td>
</tr>
<tr>
<td>Men's 7</td>
<td>57.89 (0.20)</td>
<td>3.80 (0.29)</td>
</tr>
<tr>
<td>Ladies' 1</td>
<td>57.37 (0.46)</td>
<td>3.40 (0.35)</td>
</tr>
</tbody>
</table>

Note: standard deviations given in parentheses.

Grass

Thirty-two Slazenger Wimbledon balls were collected after use in a professional grass court tournament. Tubes were collected after the ball change at nine games (not including match warm up) for men's and ladies' play during warm, dry conditions. Table 5.5 shows the mass and roughness results for the samples. No relationship between ball mass and fuzziness was explored as all samples were used for a similar number of games.

As the balls were used for a fewer number of games than collected from other surfaces, it is difficult to make direct comparisons in ball wear measures. Ball masses suggest higher values than those observed for balls used on an acrylic court surface for a similar number of games, though similar roughness values. Standard deviations for the measurements are similar to those observed for balls used during clay court play. Higher ball masses could result from less cloth being removed during court impacts or a difference in the number and types of shots occurring during play. The speed of the grass court game favours 'serve and volley' players while clay court matches generally produce longer shot rallies.

Table 5.5: Characteristics of balls used during a grass court tournament.

<table>
<thead>
<tr>
<th></th>
<th>Ladies'</th>
<th>Men's</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (g)</td>
<td>57.92 (0.43)</td>
<td>58.03 (0.22)</td>
</tr>
<tr>
<td>Roughness (mm)</td>
<td>3.54 (0.26)</td>
<td>3.84 (0.60)</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>58.05 (0.43)</td>
<td>57.70 (0.43)</td>
</tr>
<tr>
<td>Roughness (mm)</td>
<td>3.55 (0.19)</td>
<td>3.74 (0.48)</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>58.13 (0.39)</td>
<td>58.37 (0.13)*</td>
</tr>
<tr>
<td>Roughness (mm)</td>
<td>3.53 (0.42)</td>
<td>3.61 (0.40)*</td>
</tr>
<tr>
<td>Mass (g)</td>
<td>57.99 (0.27)</td>
<td></td>
</tr>
<tr>
<td>Roughness (mm)</td>
<td>3.40 (0.41)</td>
<td></td>
</tr>
<tr>
<td>Mass (g)</td>
<td>57.91 (0.42)</td>
<td></td>
</tr>
<tr>
<td>Roughness (mm)</td>
<td>3.40 (0.23)</td>
<td></td>
</tr>
</tbody>
</table>

Note: standard deviations given in parentheses.
*Balls used for 5 games.

Conclusions from Court Testing

Results suggest differences in ball mass and fuzziness due to use on differing surfaces. In addition, variations in ball logo condition and colouring were also observed. Logo condition was analysed using thresholded black and white images of each sample's logo. All images were taken under the same conditions and processed in the same manner. The number of pixels in each worn logo was calculated and compared to the value from a new ball having an identical logo. These ratios were then adjusted based on the number of games each ball was used for. The hard and clay court samples showed significantly poorer logo condition than the grass court samples ($p < 0.001$). Analysis suggests that the wearing of the ball logo during play on grass courts occurs at less than half the rate of that on hard and clay surfaces.

The clay balls exhibited general overall discoloration, while the grass samples often had regions of discoloured cloth due to staining from individual impacts. Further work monitoring individual ball mass
losses and the number and types of shots occurring during play could provide further insight into this area of ball wear.

5.2.3 Flight

Although court and racket impacts perhaps play a more significant role in ball wear, in play a ball spends the majority of its time in the air. To investigate any potential changes to ball condition caused during this stage of play, ball characteristics were monitored before and after aerodynamic wind tunnel testing. Balls were tested three times at wind speeds from 0-40ms\(^{-1}\), from 0-3000rpm. Testing time with airflow for each ball was approximately 2 hours. While it is difficult to calculate how many games or sets this accounts to in a tennis match, the information will be useful in determining if changes to ball condition do actually occur.

Four ball samples were used in tunnel testing, one from each category of textile wear identified in Chapters 3 and 4: bald, new, loose fuzz, and tufted fuzz. Images were taken for ball samples before and after testing. Figure 5.7 shows the condition of a tufted fuzz ball immediately after testing, though this surface was vacuumed before photographing. Table 5.6 shows all four balls had increases in levels of fuzz after testing, indicating airflow and spin caused an increase in ball fuzziness. It can be theorized that higher spin rates caused greater amounts of fuzz to lift from the ball surface due to centrifugal force, an outward acting reaction force proportional to an object's angular velocity (spin rate). Some of the balls also had higher standard deviations in their fuzz measurements, indicating increased numbers of outliers on the ball surfaces. An exception to this was the loose fuzz ball that showed a decrease, likely because some of the long, loose fibres originally present were removed during testing. Mass losses can be considered negligible as they are less than 1% of the original masses.

![Figure 5.7: Example of a ball immediately after wind tunnel testing.](image)

<table>
<thead>
<tr>
<th>Roughness (mm)</th>
<th>Pre-test</th>
<th>Post-test</th>
<th>Mass loss (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald</td>
<td>2.198 (0.394)</td>
<td>2.260 (0.657)</td>
<td>0.03</td>
</tr>
<tr>
<td>New</td>
<td>3.374 (0.490)</td>
<td>4.816 (0.518)</td>
<td>0.06</td>
</tr>
<tr>
<td>Loose fuzz</td>
<td>4.603 (0.707)</td>
<td>4.699 (0.681)</td>
<td>0.06</td>
</tr>
<tr>
<td>Tufted fuzz</td>
<td>4.528 (0.494)</td>
<td>4.907 (0.520)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*Note: standard deviations given in parentheses.*

5.3 Natural Factors

While wear caused by play is an obvious component to ball degradation, there are also several components of ball degradation not affected by use. These can include environmental differences, such as temperature and precipitation, and inherent differences in ball construction, such as core and cloth manufacture. The structure of these influences can be seen in Figure 5.8. Several of these components were investigated for their contributions to ball degradation.
5.3.1 Ball Construction

The rules of tennis state only minimal conditions for ball construction. Balls must meet standardised test requirements and consist of a uniform, cloth covering with stitchless seams (ITF, 2006c). Two areas of manufacturing differences were identified: core construction and cloth type.

Cloth Type

Ball fuzziness and mass loss were monitored for three cloth types: a sateen weave, a needle felt, and a sateen weave treated with Hydroguard. Hydroguard is an additive in the dyeing process used to improve the water resistance of the cloth - important for play in wet or damp conditions.

Figure 5.9 shows testing results through 500 impacts. Both sateen weave balls indicate higher rates of mass loss as compared to the needle felt ball. While the other ball types show decreased fuzziness with increased numbers of impacts, Hydroguard fuzziness levels remained constant.

The mass results differ from those presented by Capel-Davies & Miller (2003) that show greater losses from a needle felt ball and comment on the continued linear trend in mass loss through 1000 impacts. A sateen weave ball showed a slowed rate of loss over extended impacts. These differences could be due to the wearing mechanism, impact speed, or ball brand, and highlight the need for standardised wearing methods. Testing with an increased number of impacts could also provide more information into any similarities in the data sets.

![Figure 5.9: Effect of cloth type on ball wear characteristics.](image)
Core Construction

The two main core constructions in tennis, pressurised and pressureless (PL), were examined for wear differences. Both ball types were constructed with similar sateen weave cloths. Differences in standardised test results are shown in Table 5.7. The pressureless balls indicate lower forward compression, higher return compression, and lower bounce heights. There were no significant differences in the standardised test results with increased numbers of impacts ($p = 0.953$).

Figure 5.10 shows mass and fuzz trends for the differing core constructions. The pressureless ball shows an increased rate of mass loss as compared to a pressurised ball, though similar roughness values. This data supports trends found in racket testing that indicated no relationship between mass loss and fuzziness trends. Differences in mass losses could be due to ball impact properties as Haake et al. (2003) find increased contact times for pressureless balls compared to pressurised balls against rigid surfaces and with high stringing tensions. These increased contact times could contribute to higher amounts of felt being removed from pressureless balls.

5.3.2 Precipitation

Although tennis played on outdoor courts is often regulated by the weather, there are often occasions before, during, and after play where poor weather affects tennis balls. To investigate potential differences in degradation due to water, ball mass and fuzziness were monitored over 500 impacts for three cloth types (sateen weave, Hydroguard sateen weave, and needle felt).

There is no current standardised testing methodology for wet tennis balls. A standardised procedure, developed by Milliken, was used for all ball samples. Balls were completely submerged with a weight in water for five minutes, and then bounced 10 times from chest height to release excess water before wearing.

<table>
<thead>
<tr>
<th>Number of Impacts</th>
<th>Forward Compression (mm)</th>
<th>Return Compression (mm)</th>
<th>Bounce Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>PL</td>
<td>Wet</td>
</tr>
<tr>
<td>0</td>
<td>5.68</td>
<td>5.53</td>
<td>5.72</td>
</tr>
<tr>
<td>50</td>
<td>5.60</td>
<td>5.36</td>
<td>5.70</td>
</tr>
<tr>
<td>100</td>
<td>5.71</td>
<td>5.39</td>
<td>5.67</td>
</tr>
<tr>
<td>250</td>
<td>5.65</td>
<td>5.39</td>
<td>5.68</td>
</tr>
<tr>
<td>500</td>
<td>5.79</td>
<td>5.51</td>
<td>5.70</td>
</tr>
</tbody>
</table>

Table 5.7: Standardised testing results for wet and dry pressurised balls and dry pressureless balls (PL).

Figure 5.10: Effect of core construction on ball wear characteristics.
Individual ball masses were monitored before and after water absorption, as well as after wearing. Images for fuzz analysis were taken only after wearing.

Table 5.8 details the average increase in ball mass before impact testing. The Hydroguard felt showed significantly ($p < 0.001$) less water absorption while the needle felt indicated significantly higher absorption ($p < 0.001$) for all ball samples. Standardised test results for the wet samples (standard, sateen weave) are shown in Table 5.7. Testing was performed within thirty minutes of the balls being removed from the testing chamber. The most noticeable difference in the wet balls was a low pre-impact bounce height. The large initial mass loss shown in Figure 5.11(a) for the wet samples suggests their low bounce height can be attributed to excess water removed from the ball with impacts.

Both the untreated sateen weave and needle felt ball showed some irregularities after 100 impacts, but there was not enough evidence to remove these data points from consideration. After initial mass losses, the three ball types showed similar rates of loss over extended impacts and similar trends in fuzziness. Unlike dry testing, all balls showed a dramatic decrease in fuzziness after 50 impacts.

Table 5.8: Average mass increases before wet testing.

<table>
<thead>
<tr>
<th>Ball Type</th>
<th>Increase in Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular Woven</td>
<td>7.30</td>
</tr>
<tr>
<td>Hydroguard woven</td>
<td>0.48</td>
</tr>
<tr>
<td>Needle felt</td>
<td>16.59</td>
</tr>
</tbody>
</table>

![Figure 5.11](image)

5.3.3 Natural Pressure Loss

Interviews and testing with elite players has highlighted a preference for pressurised balls, citing improved feel and performance (Davies, 2005; Loughborough University Tennis Team, 2004). Pressurised balls are affected by the large pressure gradient between the ball core and atmosphere when they are removed from pressurised storage. Previous work has used punctured balls as an approximation of the changes to pressurised balls over time, though it is not known if these assumptions are appropriate (Goodwill & Haake, 2001; Haake et al., 2003).

Standardised test results for a dozen pressurised balls, along with upper and lower ITF acceptance limits, are shown in Figures 5.12(a)-5.12(c). Additionally, internal core pressure was measured using a sharpened needle connected to a digital manometer. Wall thickness was reduced using the tip of a soldering iron so the needle could be easily pushed into the ball core.

Trends indicate a higher rate of change for standardised test results during the first 30 days after opening. While forward and return compression values remain within acceptable ITF limits through 180
days, bounce heights fall out of specification after only three weeks. As higher pressure gradients generally result in higher flow rates, it is expected that the largest change in internal ball pressure, and resulting ball properties, occurs soon after opening. These static testing results also indicate that punctured balls do not approximate naturally aged balls through six months.

5.3.4 Other Factors

Temperature and altitude were also identified as naturally occurring components of ball degradation. According to the ideal gas law, a drop in temperature will also cause a corresponding decrease in pressure for a constant volume. An increase in altitude will create a similar drop in atmospheric pressure. Lower atmospheric pressures will increase the pressure gradient across the ball and corresponding rate of pressure loss from the ball core. Anecdotal evidence collected during interviews suggests players often use pressure-less balls during colder playing conditions to minimise the rate of pressure loss (Loughborough University Tennis Team, 2004).

As these two variables are not expected to affect ball mass or fuzziness, potential effects will be observed with regards to natural pressure loss, though these effects will likely alter the rate of degradation. Other effects, such as changes to the rubber core, are an area for future consideration.

5.4 Concluding Comments

Engel (1992) identifies four variables affecting wear during abrasive sliding. Wear is directly related to a
wearing coefficient, normal contact force, and sliding distance and inversely related to hardness. A higher contact force explains the increased mass loss found at a higher impact speed. The differences due to string type could be attributed to differing wearing coefficients, or perhaps hardness. The lower mass losses in the needle felt could also be due to a different wearing coefficient. The increased contact time of pressureless balls could increase the sliding distance and amount of surface wear, though this is not true for lower string tensions.

Experimental work performed in this chapter examined a range of degradation factors affecting tennis balls. Racket testing suggests variations in ball mass loss due to string type and impact speed. Play on clay courts indicates lower mass losses and increased fuzziness as compared to hardcourt play. Although there is some indication of increased fuzziness with slower rates of mass loss, no definite relationship could be established with the gathered data. The relationship between mass loss and fuzziness will vary by ball brand, construction, and play conditions. The remainder of this thesis focuses on surface differences, as opposed to mass differences, due to the visual cues it offers to players. Results obtained in testing identifies four categories of degradation for future dynamic impact testing.

Natural Ageing Observed differences in standardised testing results suggest important differences in ball properties will emerge in dynamic testing. Several levels of natural ageing were determined from initial results. New, one week, and three week samples will provide information during initial decreases in internal ball pressure, while three month, six month, and one year samples will provide information on extended gradual pressure loss. Punctured balls should also be dynamically tested for comparison with naturally aged results.

Fuzziness Differences in ball fuzziness were observed throughout the investigations conducted in this chapter. Both increases and decreases in ball fuzziness were observed with repeated impacts. To isolate ball surface condition, manual alteration of the ball surface is proposed for future testing.

Repeated Impacts While repeated impacts indicated differences in ball mass and fuzziness, standardised test results did not reveal variations in static ball characteristics. By isolating the ball core from changes to the ball covering (mass loss and fuzziness), the dynamic effects of repeated impacts on the rubber core can be observed. Impact levels used in this chapter will be considered, along with a more detailed analysis of impacts during the early stages of play as players indicate a 'loosening' of the ball.

Precipitation This is a unique factor in degradation as balls may increase in weight, but also change in fuzziness. Initial testing indicated differences between cloth types, though future testing will focus on an untreated sateen weave cloth. Several potential ball conditions rising from precipitation will be analysed. The test procedure used in this chapter (submerging samples for five minutes) will be one method used. A second sample will be created using a similar procedure, but shortening the submersion time to one minute. The final sample will be submerged for five minutes, but allowed to dry completely before dynamic testing.
Chapter 6

Ball Performance: Impacts

The dynamic nature of tennis makes ball impacts an important component of tennis ball performance. This chapter uses ball impact and rebound properties to identify differences resulting from degradation. Ball differences were investigated using three types of impacts: racket, court, and rigid plate. Several properties, including spin, COR, stiffness, damping, peak force, and contact time, were used to characterise ball impact performance for a range of ball samples. Four major areas of ball degradation were identified in Chapter 5 and are investigated in this chapter: natural ageing, fuzziness, repeated impacts, and precipitation. Sample preparation, experimental testing setups, and test results are discussed in this chapter.

6.1 Test Development

Testing incorporated several ball conditions and experimental setups to fully characterise ball properties. Ball processing and testing configurations are discussed in this section, with full details of equipment specifications and calibration given in Appendix E.

6.1.1 Ball Degradation Characteristics

All balls were opened in advance of testing, stored in controlled conditions, and pre-compressed according to ITF ball testing specifications (ITF, 2006c). Appropriate levels in each area of degradation were identified through work in Chapter 5, with three balls prepared for each sample condition. Processing methods were carefully controlled and documented to ensure consistent, repeatable results.

Natural Ageing

Pressurised tennis balls are generally preferred to pressureless balls, as players cite improved feel and sound (Davies, 2005). Testing involving naturally aged balls looks to improve on previous work limited to punctured balls, though a punctured ball will also be tested for comparison with previous results. Six levels of natural ageing were determined appropriate for testing, with standardised test results detailed in Table 6.1. These samples are expected to provide information during both initial phases of pressure loss and differences occurring with extended natural ageing. Dunlop Tournament balls were opened at appropriate intervals in advance of testing and stored in a controlled environment until required.

Fuzziness

Differences documented in Chapter 5 and anecdotal evidence noted by players support the importance of ball fuzziness in tennis. While the effects of ball fuzziness have been widely examined in aerodynamics, its importance during impacts has yet to be determined.

Ball fuzz levels were artificially created for testing to eliminate any residual effects occurring with repeated impacts and other wearing methods. Pressurised Dunlop Tournament balls were modified to
Table 6.1: Standardised test results for naturally aged balls used in dynamic testing.

<table>
<thead>
<tr>
<th></th>
<th>Fwd. Cmp. (mm)</th>
<th>Ret. Cmp. (mm)</th>
<th>Bounce (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>6.22 (0.16)</td>
<td>8.48 (0.28)</td>
<td>143.00 (0.71)</td>
</tr>
<tr>
<td>1 week</td>
<td>6.53 (0.30)</td>
<td>8.82 (0.49)</td>
<td>136.33 (3.61)</td>
</tr>
<tr>
<td>3 weeks</td>
<td>6.71 (0.26)</td>
<td>9.36 (0.32)</td>
<td>134.75 (2.73)</td>
</tr>
<tr>
<td>3 months</td>
<td>6.66 (0.39)</td>
<td>9.57 (0.59)</td>
<td>132.50 (3.37)</td>
</tr>
<tr>
<td>6 months</td>
<td>6.98 (0.38)</td>
<td>10.25 (0.48)</td>
<td>125.17 (4.39)</td>
</tr>
<tr>
<td>12 months</td>
<td>7.08 (0.12)</td>
<td>11.35 (0.29)</td>
<td>124.37 (1.22)</td>
</tr>
<tr>
<td>Punctured</td>
<td>7.65 (0.28)</td>
<td>15.58 (0.48)</td>
<td>111.57 (0.50)</td>
</tr>
</tbody>
</table>

Note: standard deviations given in parentheses.

Repeate d Impacts

To isolate the effects of repeated impacts and eliminate additional mass and fuzziness changes occurring with wear, pressurised ball cores were selected for testing. A cyclical wear rig, consisting of a BOLA ball machine and two oblique impacts, was developed to impact the balls. Figure 6.2 shows the racket stringbed and steel plate used in wearing. Impacts were recorded with a laser counter placed at the mouth of the ball machine.

Four impact levels were identified in Chapter 5 for examining repeated impacts: 50, 100, 250, and 500 impacts. To investigate perceptions that the ball 'loosens' during the initial stages of play, additional data will be gathered for balls receiving less than 100 impacts (at 25, 50, 75, and 100 impacts). As the wear

Table 6.2: Characteristics of fuzzy balls used in dynamic testing.

<table>
<thead>
<tr>
<th>Processing</th>
<th>Fwd. Cmp. (mm)</th>
<th>Ret. Cmp. (mm)</th>
<th>Bounce (cm)</th>
<th>Mass (g)</th>
<th>Roughness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Bald</td>
<td>6.29 (0.15)</td>
<td>8.44 (0.33)</td>
<td>146.0 (1.32)</td>
<td>56.01 (0.72)</td>
<td>2.18 (0.39)</td>
</tr>
<tr>
<td>Bald</td>
<td>6.31 (0.23)</td>
<td>8.76 (0.32)</td>
<td>142.9 (2.03)</td>
<td>57.22 (0.04)</td>
<td>2.72 (0.20)</td>
</tr>
<tr>
<td>New</td>
<td>6.22 (0.16)</td>
<td>8.48 (0.28)</td>
<td>143.0 (0.71)</td>
<td>57.90 (0.54)</td>
<td>4.40 (0.41)</td>
</tr>
<tr>
<td>Fuzzy</td>
<td>6.27 (0.23)</td>
<td>8.73 (0.33)</td>
<td>141.1 (1.36)</td>
<td>58.01 (0.30)</td>
<td>5.93 (0.64)</td>
</tr>
<tr>
<td>Very Fuzzy</td>
<td>6.60 (0.21)</td>
<td>8.89 (0.27)</td>
<td>137.8 (4.00)</td>
<td>58.27 (0.33)</td>
<td>5.71 (0.64)</td>
</tr>
</tbody>
</table>

Note: standard deviations given in parentheses.
rig is located in the same facility as the ball cannon, dynamic testing was completed within 20 minutes of balls receiving impacts. Wearing was performed in 50 impact repetitions, with a 5 minute rest period between cycles. This was to prevent cores from overheating and bursting.

**Precipitation**

The importance of environmental conditions in tennis and the lack of information available on this subject make it an interesting area for investigation. No work currently exists for balls used in wet conditions, despite the majority of tennis play occurring outdoors.

Three forms of ball processing were developed to simulate a range of ball conditions. Dunlop Tournament pressurised balls, with a standard sateen weave cloth, were used in testing. One group of balls was submerged for five minutes, a second group for one minute, and both bounced ten times from chest height before testing. The final set of balls was submerged for five minutes, bounced ten times from chest height, and allowed to dry completely before being tested. Details of the balls are shown in Table 6.3, with post test mass results indicating minimal water loss during testing. An unmodified ball was also tested for comparison. Balls were used for no more than eight impacts and tested within a 15 minute time interval to minimise water loss during testing. The order of testing speeds was also randomised to prevent any artificial trends from appearing due to water loss.

These processing methods were developed to represent several possible conditions. The five minute soak could reflect a ball being left in the rain overnight, with samples played with when wet and after drying. The one minute soak is more similar to a new ball absorbing water during play in wet conditions. It is suggested that manufacturers and governing bodies could benefit from a standardised method of simulating play during wet conditions. This method could incorporate a dry ball impacting a wet surface.

| Wet-1min | 1.72 | 0.38 |
| Wet-5min | 6.98 | 1.24 |
| Wet-dried | 0.12 | 0.05 |

**Table 6.3: Characteristics of wet balls used in impact testing.**
6.1.2 Testing Configurations

The range of properties under investigation necessitated several testing configurations. Rebound properties, including ball spin and COR, were assessed using a rigidly mounted steel plate and an oblique, head-clamped racket. Impact properties, incorporating stiffness, damping, contact time, and peak force, were determined from force-time curves recorded during ball impacts with an acceleration plate. Bounce and frictional differences were recorded on several court surfaces using a Sestée machine developed to assess court surface pace. All impacts used a pneumatic air cannon to project balls. Further information on experimental equipment is detailed in Appendix E. New techniques were used in the collection of the data to improve upon previous results. Automated ball tracking improved COR results by using ten times the number image frames used by other authors (Cottey, 2002; Goodwill & Haake, 2004b). An acceleration plate also produced force data with less noise than observed in previous investigations (Davies, 2005).

Rebound Properties

An oblique racket impact was used to assess ball spin and speed after impact. As the air cannon produces less than 70rpm of inbound spin, outbound spin measurements will be used to determine ball spin generation (Cottey, 2002). Ball COR in the normal direction ($e_y$) was measured for both an oblique racket impact and a normal impact with a rigid plate. This rigid impact will be used to compare data with previously conducted research.

A Dunlop 200G racket was strung with 18 mains and 20 crosses at 27.3kg for testing. This tension was selected as higher tensions produce greater differences in dynamic ball properties (Haake et al., 2003). The racket was strung with synthetic gut string with a 1.40mm diameter. Testing was performed between five and twelve days after initial stringing as the racket retains approximately 80% of its initial stringbed stiffness during this period (Cottey, 2002). The racket head was also rigidly clamped as Haake et al. (2000a) find better differentiation between balls with a rigidly clamped racket head as compared to a freely suspended racket.

A 40° racket angle produces consistent angular and rebound velocities and has been used in previous research. Over a range of inbound speeds, there is also a strong correlation between angular velocity and rebound velocity for angles less than forty-five degrees (Bao et al., 2002; Cottey, 2002). Two testing speeds were used to assess the importance of impact speed in rebound performance as racket strings can embed in the ball cloth (Ashcroft & Stronge, 2002). Balls were fired at 20.9 ms$^{-1}$ ($\sigma = 0.84$) and 35.9ms$^{-1}$ ($\sigma = 1.13$), with the lower speed approximating a volley or ground stroke and the higher speed used by Cottey (2002) to examine spin differences in oblique racket impacts. Two dozen impacts were recorded for each ball type at each testing speed. It should be noted that COR measurements ignore the effect of energy lost to spin during racket rebound. Attempts to calculate tangential COR values that incorporate spin ($e_x$) produced inconsistent results. Further work in this area is more fully discussed in Chapter 11.

Rigid plate testing included three impacts at 5ms$^{-1}$ increments from 15-45ms$^{-1}$. This range of speeds is seen to encompass the majority of shots played in tennis (Pallis, 1999b). Additional testing (two dozen impacts) was performed for ball cores receiving less than 100 impacts at 30.9ms$^{-1}$ ($\sigma = 1.23$). It should be noted that isolated testing speeds, as opposed to a range of speeds, were used for racket impacts and some core testing due to inconsistent results observed during impacts over a range of speeds.

Impact Properties

Contact time, peak force, stiffness, and damping for normal ball impacts were calculated from force data for speeds from 15-45ms$^{-1}$. While peak forces and contact times can be determined directly from the force data, an analytical model must be used to calculate ball stiffness and damping values.

Two main impact models have been used in previous work. The simplest viscoelastic impact model is the Kelvin-Voigt model, using a spring and damper in parallel, shown in Figure 6.3(a) (Dignall & Haake, 2000; Goodwill & Haake, 2001). Goodwill & Haake (2004c) improved this model with an additional
damping component to account for momentum flux loading. This model shows errors of less than 10% with recorded impacts, but relies on experimentally determined data, including contact time and ball COR, to produce results. As a non-rigid acceleration plate was used to measure force data, ball COR data would be required from an alternative testing setup, introducing curve fitting errors and speed approximations to calculations.

Davies (2005) calculated stiffness and damping parameters with a Kelvin-Voigt model directly from a force profile, using a method developed by Babitsky & Veprik (1998). Further work performed by Turner (2005) has investigated a multi-degree of freedom model, shown in Figure 6.3(b), and alternative spring models including a linear Hooke’s spring, spherical Hertzian spring, and combination spring. The linear spring produces a force according to $F = k_s x$, while the Hertzian spring is governed by the relationship $F = k_s x^{3/2}$ (Stronge, 2000). A combined spring, incorporating differing characteristics in the compression and rebound phases of impact, was also modelled with results shown in Figure 6.4. While the multi-degree of freedom model most accurately reflects the components of the ball, further work is still required to improve model fit to experimental data. Data fitting for impacts performed in this chapter utilised a Hertzian spring as this was found to minimise model error and has been used in other viscoelastic ball impact modelling (Cochran, 1998; Haake, 1991; Jones, 2002).

Parameter optimisation utilised the gradient descent method to minimise the mean squared error for the model. The gradient of errors due to small changes in the stiffness and damping parameters determines optimal values (Turner, 2005). Initial stiffness values were calculated by approximating the impact as a half sine wave and determining the contact time for the impact. The starting damping value was calculated from initial impact forces and the ball’s inbound speed. Model force and displacement values were calculated according to the central difference method. Displacement, $x$, is determined through a recurrence formula with an initial value $x_0$ given in Equation 6.1. Displacement calculated according to Equation 6.2 can then be used to calculate the force during impact, shown in Equation 6.3. The Hertzian spring model averaged 12.7% error over all impacts.

\[

dots
\]

**Court Surface Impacts**

Court surface pace is considered relevant to player assessment of incoming ball speed and bounce height. Previous work, however, has focused on classifying court surface differences using standard tennis balls (Cox, 2003). A pilot study was developed to assess differences in the ball-court interaction due to ball degradation. Impacts were recorded on two acrylic courts, an artificial turf surface, and a green clay court.

Experimental work was performed according to ITF specifications for court surface measurement, though only a single impact location was used (ITF, 2006c). Impacts were recorded between the tram lines of the singles and doubles court and average values computed from three impacts for each of three ball samples. Balls were projected onto the court surface at an angle of $16\pm2^\circ$ with a speed of $30\pm2\text{ms}^{-1}$. These conditions allow for the assumption that the ball slides throughout impact and the coefficient of sliding friction to be determined. Three properties were assessed using the Sestee machine: the normal and tangential coefficient of restitution and the coefficient of sliding friction. Further details concerning these measurements are located in Appendix E.
6.2 Results

This section presents rebound, impact, and court testing results conducted in this chapter. Significant differences for cores receiving less than 100 impacts and tested at a single speed were calculated with single factor ANOVA test. A two factor ANOVA test incorporating all collected data was used to determine significant differences in racket COR and spin results performed at two testing speeds. Testing performed for COR and impact properties over a range of testing speeds (from 15-45ms⁻¹) were fit with a best fit polynomial curve due to the volume of data points. The 95% confidence interval for each curve was used to determine significant differences between samples. Significant differences in court impact properties were examined using a two factor ANOVA test including data from all four test court surfaces. Multiple comparison procedures for significantly different results are discussed in Appendix C.

6.2.1 Rebound Properties

Ball COR and spin data were collected from oblique racket impacts and normal impacts with a rigidly mounted steel plate. Naturally aged, fuzzy, and wet balls were tested with both testing setups. Cores were only used with the rigid plate setup as pilot testing indicated inconclusive and highly variable racket rebound results. All racket COR and spin results were significant ($p < 0.001$) when data from both testing speeds (20 and 35ms⁻¹) was considered.

A summary of results is presented in Table 6.4, with data given in Figures 6.5-6.8. New ball COR results show good agreement with Cottey (2002) at 35ms⁻¹, though the new and punctured balls indicate
slightly higher COR values than those found by Haake et al. (2003) at 20ms$^{-1}$. This can be explained by the higher string tension (31.7kg) used by Haake et al. (2003) and the lower rebound velocities produced by higher string tensions. The spin produced by the new ball is approximately 200rpm higher than that reported by Cottey (2002). Rigid plate COR results show good agreement with data collected by Haake et al. (2003) in Figure 6.14(a), though the new ball has consistently lower COR values through the range of testing speeds.

Newer balls generally produced higher spin values during racket testing, though COR results showed more variation. Bald balls also indicated higher COR values, though data indicated that new and fuzzy balls produced higher amounts of spin. The tufted fuzz on the very fuzzy ball could have affected the ball’s interaction with the stringbed and limited its outbound spin. The low spin results for the the one week and very fuzzy balls were verified through retesting. Drier balls tended to produce lower COR values and higher outbound spin. Results from rigid plate testing indicate the stringbed could mask differences in ball COR.

### 6.2.2 Impact Properties

Ball stiffness, damping, peak force, and contact time values were calculated from the acceleration plate data. Significant differences were again examined according to the 95% confidence intervals on the best fit curves. It is theorised that further statistical differences may exist if balls are examined at a single testing speed. Naturally aged balls generally required 6-12months (or a puncture) to produce significantly different measurements, though results showed good trends with regards to age. Wet balls also showed good differentiation, though there were no significant differences between the curves for the fuzzy or repeated impact (0-500) balls. Repeated impacts (0-100) tested only at 30ms$^{-1}$ indicated differences in impact properties with decreased stiffness and peak force after initial impacts. Results are discussed in Table 6.5 and shown in Figures 6.9-6.13.

#### Comparison with Previous Work

Haake et al. (2003) document impact properties of several tennis balls with rigid plates and head clamped rackets. A comparison to data collected in this chapter is shown in Figure 6.14. Stiffness values are larger for both punctured and new tennis balls, with a larger difference between the two balls. Damping results indicate a slower rate of change with regards to impact speed, though show a similar magnitude of separation between the two balls. Contact time shows very good agreement with previous results. The authors also use a single degree of freedom model, though rely on experimentally determined contact time and COR data to determine stiffness and damping parameters. Peak forces reported by Haake et al. (2003) for pressurised and punctured ball impacts between 15-25ms$^{-1}$ are also slightly higher than those recorded in this investigation.

### 6.2.3 Court Impacts

Court impacts were assessed using data recorded with the Sestée machine. Data for four surfaces, including two different hard courts, was collected during the pilot study and is displayed in Figures 6.15-6.17. Nine impacts were recorded for each ball type on each surface, though data for the green clay surface is limited due to problems with surface deterioration during extended testing. For all measured properties, the clay court produced data values significantly different than both the acrylic court and artificial surfaces. With the data that was recorded, the clay results also suggested much larger differences between balls. This suggests that differences in court interactions may be more significant, and perhaps more noticeable to players, on a clay court as compared to a hard or artificial surface. Table 6.6 shows p-values for the three properties measured during court impacts. Values below 0.05 indicate significance at the 95% confidence level.
Table 6.4: Summary of rebound results for tested ball samples.

<table>
<thead>
<tr>
<th>Natural Aged</th>
<th>Plate COR</th>
<th>Racket COR</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Figure 6.5)</td>
<td>6 month, 12 month, and punctured samples significantly lower COR than all other balls. Three month ball showed improved differentiation from newer balls at speeds below 30ms(^{-1}).</td>
<td>3 week and 12 month balls significantly higher COR, punctured significantly lower. No consistent trends with increasing ball age. Punctured ball is only sample with higher COR at higher testing speed.</td>
<td>New balls produced significantly more spin; punctured and 12 month ball significantly less. Punctured ball also had significantly less spin than the 12 month ball. Spin from 1 week and 6 month balls significantly less than new, 3 week, and 3 month balls.</td>
</tr>
<tr>
<td>Fuzzy (Figure 6.6)</td>
<td>No significant differences.</td>
<td>Greater differences between balls at higher testing speed. Generally lower COR with increased ball roughness. The very bald ball had a significantly higher COR than the new, fuzzy, and very fuzzy balls.</td>
<td>Minimal trends with regards to increased spin and ball roughness. The very fuzzy ball produced significantly less spin than all other balls</td>
</tr>
<tr>
<td>Repeated Impacts (Figure 6.7)</td>
<td>0-500</td>
<td>No significant differences.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-100</td>
<td>No significant differences.</td>
<td></td>
</tr>
<tr>
<td>Precipitation (Figure 6.8)</td>
<td>New ball showed significantly lower COR than all other samples.</td>
<td>General trend of increasing COR with increasing water on the ball. Two balls tested when wet had a significantly higher COR.</td>
<td>The wet balls had significantly lower spin rates the new and dried balls. General trend of less spin with increasing water on the ball.</td>
</tr>
</tbody>
</table>
Figure 6.5: Rebound properties for naturally aged balls.
Figure 6.6: Rebound properties for fuzzy balls.

Figure 6.7: COR for repeated impacts (cores).
Figure 6.8: Rebound properties for wet samples.

(a) Racket COR.

(b) Spin.

(c) Rigid plate COR.

Figure 6.9: Impact properties for naturally aged balls.

(a) Stiffness.

(b) Damping.

(c) Peak force.

(d) Contact time.
<table>
<thead>
<tr>
<th>Table 6.5: Summary of impact results for tested ball samples.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stiffness</strong></td>
</tr>
<tr>
<td>Natural Ageing</td>
</tr>
<tr>
<td>Fuzzy (Figure 6.10)</td>
</tr>
<tr>
<td>0-500 (Figure 6.11)</td>
</tr>
<tr>
<td>Repeated Impacts</td>
</tr>
<tr>
<td>0-100 (Figure 6.12)</td>
</tr>
<tr>
<td>Precipitation (Figure 6.13)</td>
</tr>
</tbody>
</table>
Figure 6.10: Impact properties for fuzzy balls.

Figure 6.11: Impact properties for repeated impacts (cores).
Figure 6.12: Impact properties for less than 100 repeated impacts (cores).

Figure 6.13: Impact properties for wet samples.
When considering results from all the surfaces, no significant differences in the aged and fuzzy samples were recorded for the coefficient of sliding friction and horizontal COR. The bald ball had a significantly higher vertical COR than the fuzzy ball. The new and three week ball had significantly higher vertical COR values than the three month ball. These results suggest the 'speed' of the court surface was not affected by ball condition, but the height and speed of the vertical bounce did produce differences.

Results from this pilot study can be useful in developing further testing, especially focused on oblique impacts. It is suggested that future testing utilise at least three different court surfaces, a larger range of test samples, and record larger numbers of impacts with each ball type. Further discussion of oblique impacts is presented in Chapter 11.

### 6.3 Evaluation of Results

This chapter provides impact testing data for four types of ball degradation. Impact results suggest generally increased peak forces from newer balls and those with heavier masses. In several instances one week aged and very fuzzy balls produced inconsistent results, though samples were retested and similar results recorded. General trends for each of the four ball conditions are summarised below.
Figure 6.15: Vertical COR.

Figure 6.16: Horizontal COR.

Figure 6.17: Coefficient of sliding friction.
Natural Ageing Racket impacts suggest newer balls generally produce more spin, though COR results were varied. With rigid plate impacts, balls six months and older indicated significantly lower COR values. Balls generally showed a decrease in stiffness and peak force, and an increase in damping and contact time, with age.

Fuzziness New and fuzzy balls indicated increased spin during racket impacts, though the very fuzzy ball did not. At slower testing speeds, fuzzy balls had slightly longer contact times. Ball fuzz affected ball COR and balder balls have higher values.

Repeated Impacts Isolated testing on balls receiving less than 100 impacts produced the most conclusive results as new balls showed increased stiffness and peak forces. The lack of decisive results for increased numbers of impacts (over 100) suggests that rubber fatigue and deterioration is not a major component in ball degradation.

Precipitation The two wet balls tested both produced less spin, but higher COR values during racket testing. This suggests that water may affect friction between the cloth and stringbed, with a reduced ability to produce spin.

Although the wet balls did indicate good differentiation during testing, they are impractical for use during indoor player testing. As limited differences were recorded for cores sustaining repeated impacts, it is suggested that player testing utilise naturally aged and fuzzy samples. Significant differences in naturally aged balls generally occurred after six months, or with punctured balls. The length of this time period can be considered longer than a the average lifespan of balls. The average spending by tennis players on tennis balls (£23/year) suggests purchases of five to six tubes of ball per year (LTA, 2004). For this reason, it is suggested player testing utilise balls aged three months and under. The surprising differences in some properties between fuzzy and very fuzzy balls suggest that both these fuzz types should be included in perception testing.

6.4 Player Testing Samples

While trends in impact testing through a range of impact speeds can be determined from much of the data presented in this chapter, player testing will utilise shots performed at isolated testing speeds. To provide improved objective data for comparison with subjective results, further impacts were recorded at 20 and 35ms⁻¹ to simulate the ground stroke and serve used in player perception testing performed in Chapter 9. These speeds are slightly slower than those observed by Pallis (1999b) to account for both male and female players during testing, as well as the nature of the test environment as it is unlikely players were executing shots at maximum velocity. Full details of shot selection and ball processing are detailed in Section 9.1.

Previously conducted oblique racket impacts assessing ball rebound speed and spin were combined with acceleration plate and rigid plate impacts to produce several objective measures of ball performance. Results are presented in Figures 6.18 and 6.19. Unlike in Section 6.2 where both testing speeds were used with a two-way ANOVA to determine significance, data was analysed at each testing speed independently. This was done to account for the independence of the two shots used in player testing.

Racket testing showed generally increased COR with lower ball fuzziness. The fuzzy ball COR is significantly lower than the very fuzzy and new ball at the groundstroke speed and both fuzzy balls were significantly lower than the other balls at the service speed. There was a general trend of increased spin with increased fuzziness at both speeds, though the very fuzzy ball produced significantly less spin in both instances. The fuzzy ball produced significantly more spin than the bald ball at the service speed. Racket COR for the naturally aged balls produced mixed results as the new ball was significantly lower than all balls at the lower speed, but higher than the one week and three month balls at the service speed. The aged balls showed a general increase in spin with newer balls, with the new ball producing significantly more spin than all other aged balls.
Figure 6.18: Properties for fuzzy balls used in player testing.
Figure 6.19: Properties for naturally aged balls used in player testing.
Rigid plate COR showed no significant differences for the aged balls at either speed, and only at the higher speed was the new ball significantly lower than the fuzzy ball.

Acceleration plate testing produced stiffness, damping, peak force, and contact time measurements for evaluation with perception results. The fuzzy balls showed no differences in stiffness at either speed, though the bald ball had significantly less damping than both fuzzy balls at the service speed. There was a general trend of increased damping and increased peak force (except for the very fuzzy ball) with increased fuzziness. The service speed indicated the bald ball had a significantly lower peak force than all other balls, though this is attributed to its lower mass. The very fuzzy ball had a significantly greater contact time than the bald ball at the higher testing speed, indicative of a trend of increased contact times with increased fuzziness. Naturally aged balls indicated generally more damping with increased age, though no significant differences were measured at either speed. The three month aged ball had a significantly lower stiffness and lower peak force at both testing speeds. The one week ball also indicated lower peak forces than the new and three week balls at both speeds.
Chapter 7

Ball Performance: Flight

This chapter presents three areas of testing performed to characterise differences in ball flight caused by degradation: wind tunnel drag force measurements of static and spinning balls, high speed video analysis of ball fuzz orientation, and trajectory simulation of ball flight. This work focuses on fuzz drag, a concept developed by Mehta & Pallis (2001a) to explain the importance of ball fuzz length and orientation on flight properties. Fuzz drag can be considered the additional drag force on a ball due to differences in surface characteristics and fuzz orientation. Previous work has documented both static and spinning force measurements for a wide range of tennis balls. There is no method, however, to objectively relate these differences in ball surface condition to measured results. This chapter details static and spinning force measurements for a range of tennis balls and their relationship to the developed digital fuzziness metric (DFM). Differences in ball fuzz orientation throughout a range of wind speeds and spin rates were examined using high speed imaging and the digital fuzziness metric. Finally, experimental results were used to develop an improved ball trajectory simulator.

7.1 Force Testing

Static and spinning force measurements conducted by other authors are fully discussed in Chapter 2. Similar testing was pursued in this chapter using a wind tunnel with a maximum airspeed of 45ms\(^{-1}\), suitable for evaluating ball speeds in the modern game (Pallis, 1998b). In addition to static testing, a spin rig was developed to spin ball samples up to 3000rpm and create test conditions similar to those found in play.

7.1.1 Tunnel Specifications

The tunnel available for use at Loughborough University was originally developed for scaled automotive and aeronautical testing. Force measurements are made with a six component, virtual-centre, Aerotech balance with respective working range and calibration accuracies for drag and lift forces of \(\pm 120\)N (\(\pm 0.012\)N) and \(\pm 420\)N (\(\pm 0.021\)N). During testing and sting calibration, repeatability tests suggest overall accuracies of \(\pm 0.1\)N due to experimental variation. This equates to approximately \(\pm 5\)% of the net drag force and \(\pm 3\)% of the net lift force.

The tunnel possesses a large working section (1.92m\(\times\)1.32m\(\times\)3.6m) that eliminates blockage effects found in smaller tunnels. Turbulence intensity at the midpoint is 0.15%. Velocity variation at the working section midpoint is less than 0.2% at 40ms\(^{-1}\) with a boundary layer thickness of 60mm. Samples were mounted above this layer to ensure steady airflow during testing. One hundred samples were averaged over a 20 second interval for each recorded data point. Testing included wind speeds from 0-45ms\(^{-1}\) with spin rates up to 3000rpm.
7.1.2 Static Sting

Initial testing utilised a range of rigidly mounted ball samples. The support looked to minimise effects on data collection by supporting the ball from behind. This sting is shown in Figure 7.1(a), with the ball interface in the wake of the ball. Balls were secured with a threaded stud attached to a 16mm steel bar. This bar provided the interface to the force balance mounted below the tunnel and is similar to those used in previous testing (Chadwick & Haake, 2000b; Sayers, 2003).

Force measurements are typically taken on the sting without a ball present to determine reference values. To account for flow around the ball and provide improved reference data, another support was constructed to position the ball in front of the testing sting, as shown in Figure 7.1(b). This method was tested with four different ball samples to ensure consistent reference values over the range of testing samples.

Details of balls used with this sting are given in Table 7.1. Samples were selected to represent a range of conditions resulting from play, including a twelve panel prototype ball. A smooth sphere (66mm diameter) was also tested to confirm the suitability of the support system. Ball diameter measurements were taken with calipers according to the method specified by Mehta & Pallis (2001a) and Goodwill & Haake (2004a). Balls were gripped with Vernier calipers and slowly released. The diameter measurement was recorded when the ball fell from the calipers under its own weight. Two runs were averaged for each ball and all balls had sateen weave coverings.

7.1.3 Spinning Sting

The spinning sting supported the ball from below, with a support shaft developed to accommodate added lift and out-of-balance forces. Ball samples were filled with a two-part pu expandable foam and rigidly mounted to a 16mm shaft. This shaft was then connected to a 20mm shaft leading to the motor and bearing assembly. The motor has a maximum speed of 4500 ± 10rpm with speed control performed using direct modulation of the motor current. The entire test apparatus is assembled on the underfloor balance to provide direct measurement of aerodynamic loads. This assembly is shown in Figure 7.3.

Preliminary testing highlighted concerns with vibration, natural frequencies within the system, and out-of-balance forces on the ball. Vibration on the motor-bearing assembly was monitored to prevent large forces being transmitted to the balance. Figure 7.4 shows the sharp increase in values after 3000rpm. A 10mm shaft was used to minimise the effects of any out of balance forces. Further information on the development of the spinning rig is given by Tuplin et al. (2005). Both static and spinning testing were performed for the four balls shown in Table 7.2, as well as a smooth sphere. These four balls were also all covered with a sateen weave cloth.

![Figure 7.1: Ball support systems.](image-url)
Figure 7.2: Diagram of spin rig.

Figure 7.3: Motor and bearing assembly mounted below tunnel floor.

Figure 7.4: Results of preliminary shaft vibration observations.
Table 7.1: Balls used in static testing.

<table>
<thead>
<tr>
<th>Ball</th>
<th>Size (mm)</th>
<th>Roughness (mm)</th>
<th>Image</th>
<th>Fuzz Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64.98</td>
<td>4.935</td>
<td></td>
<td>New</td>
</tr>
<tr>
<td>2</td>
<td>64.67</td>
<td>4.477</td>
<td></td>
<td>Tufted</td>
</tr>
<tr>
<td>3</td>
<td>64.87</td>
<td>4.786</td>
<td></td>
<td>Tufted</td>
</tr>
<tr>
<td>4</td>
<td>63.86</td>
<td>3.968</td>
<td></td>
<td>Bald</td>
</tr>
<tr>
<td>5</td>
<td>64.97</td>
<td>5.553</td>
<td></td>
<td>New</td>
</tr>
<tr>
<td>6</td>
<td>67.99</td>
<td>5.264</td>
<td></td>
<td>Loose</td>
</tr>
<tr>
<td>7</td>
<td>64.42</td>
<td>5.142</td>
<td></td>
<td>New</td>
</tr>
<tr>
<td>8</td>
<td>64.67</td>
<td>3.493</td>
<td></td>
<td>Loose</td>
</tr>
<tr>
<td>9</td>
<td>64.73</td>
<td>3.771</td>
<td></td>
<td>Bald</td>
</tr>
</tbody>
</table>

7.2 Evaluation of Testing Setups

A smooth sphere was used to gather reference data for each sting. Figure 7.5 shows the results of static testing compared with data collected by Achenbach (1972). Differences from standard results can be attributed either to measurement error or interference from the the support sting. As the balance has been calibrated in other applications, errors were deemed to be a result of interference from the support sting.

Chadwick & Haake (2000b) and Sayers (2003) both use similar static support systems and find results ranging between 4-14% below those documented by Achenbach (1972). Results in Figure 7.5(a) are also similarly low, but show good agreement with previously conducted research. Only Mehta & Pallis (2001a) find nearly identical smooth sphere results for their experimental system using a smaller scale tunnel and an aerofoil shaped sting. Goodwill & Haake (2004a) attribute higher reference values found with a spinning
system to support interference.

The spinning data for the smooth sphere in Figure 7.6 shows a similar shape to that gathered by Maccoll (1928), though as with the static testing, this sting produces higher drag values. The spin coefficient is the non-dimensional ratio of rotational to linear velocity used to characterise aerodynamic measurements of spinning objects. The variations in lift coefficients shown in Figure 7.6(b) are due to the varied testing speeds used. Maccoll’s reference data is taken at 10m/s for $S < 1.0$ on a 12.7mm sphere. The spin rig support is larger than the recommended 10% of ball diameter, likely introducing differences in force measurements and airflow patterns. A smaller sting was unable to be used due to the conditions of tunnel access. It is suggested that this sting could be improved in future implementations using a rigidly mounted airfoil around the spinning shaft.

While each of the stings indicates interference, the introduced errors are systematic and will affect all balls equally. Relative differences between balls will still provide useful data for comparison.

7.3 Drag Force Results

Static and spinning results for the two groups of previously detailed tennis balls are presented in this section. Results show good agreement with other authors and a strong relationship with the developed fuzziness metric. It should be noted that all testing was performed within the constraints allowed by tunnel access. Areas of further work resulting from these results are discussed in Chapter 11.

7.3.1 Static Results

Testing performed with the static sting is shown in Figure 7.7(a). The drag coefficients range from approximately 0.52 to 0.63, comparable to other published work for tennis balls with multiple trials indicating good repeatability. The data is colour coded in Figure 7.7(a) to indicate the type of fuzz on each sample. Bald balls are shown in green, new balls in black, loose fuzz in red, and tufted fuzz in blue. Generally drag coefficients increase in this order of fuzziness, with the exception being the oversized ball 6. There is no ready explanation for this difference, though manufacturing differences could have provided varied fibre characteristics.

Figure 7.8 shows that results display good agreement with the data presented by Goodwill & Haake (2004a), but are slightly higher than those documented by Mehta & Pallis (2001a). The lower values achieved by Mehta & Pallis (2001a) could be due to the higher reference values produced by their sting and subtracted from collected data.

The four fuzz types show the same ordering of drag coefficients when tested with the spinning sting. Both the magnitude and range of values in Figure 7.7(b) is much greater than with the static support system. These magnitude differences prevented DFM and drag results from being directly compared to data collected with the static sting. Results were instead adjusted to the average roughness and drag coefficient produced by the new balls in each setup. These adjustments in Figure 7.9 indicate a similar elliptical relationship to that shown in Figure 4.4. As drag data collected from a range of aerodynamic setups will inevitably produce varied results due to measurement errors and sting interference, this comparison method is suggested for use in future work.

7.3.2 Spinning Results

The drag and lift coefficients for the four ball types tested with the spin rig are shown in Figure 7.10. These values are average of three runs, throughout which all balls indicated good repeatability.

The lift coefficients fall within the range published by Goodwill & Haake (2004a) for several worn tennis balls. Results do not indicate any differences between ball types with regards to the lift coefficient and Magnus force produced for a given ball size. This means that a given spin rate will affect all balls similarly. As with the static testing performed with the spin rig, the drag values are noticeably higher than
Table 7.2: Balls used with spinning sting.

<table>
<thead>
<tr>
<th>Ball</th>
<th>Size (mm)</th>
<th>Roughness (nm)</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald ball</td>
<td>64.09</td>
<td>2.260</td>
<td></td>
</tr>
<tr>
<td>New ball</td>
<td>64.21</td>
<td>4.699</td>
<td></td>
</tr>
<tr>
<td>Loose fuzz</td>
<td>64.78</td>
<td>4.907</td>
<td></td>
</tr>
<tr>
<td>Tufted fuzz</td>
<td>63.70</td>
<td>4.611</td>
<td></td>
</tr>
</tbody>
</table>

![Image of balls with sizes and roughness values]

(a) Static sting.  
(b) Spinning sting.

Figure 7.5: Smooth sphere results for static testing.

(a) Drag data.  
(b) Lift data.

Figure 7.6: Smooth sphere results for spinning measurements.
Figure 7.7: Static testing results.

Figure 7.8: Comparison of previous results with data collected using static sting.
Figure 7.9: Spinning samples included in elliptical aerodynamic relationship.

Figure 7.10: Spinning measurements taken for the sample balls.
previously documented results (Goodwill & Haake, 2004a). The differences between the bald and new balls and tufted and loose fuzz values are similar to those achieved during static testing. Spinning testing does not indicate measurable differences between the new and loose fuzz balls, however. By introducing spin to a ball during play, the flight differences between a new ball and one with loose fuzz can be considered negligible. These results suggest that continued wear, and the development of tufted fuzz or a balding ball, are necessary to create aerodynamic differences to balls during play.

The DFM shows a good ability to use ball roughness values to predict static drag coefficients, though the addition of spin changes drag properties for loose fuzz balls and eliminates performance differences. Chapter 11 discusses areas of further work to relate both static and spinning drag forces to the DFM.

### 7.4 High Speed Video Analysis

Mehta & Pallis (2001a) present a theory for the contribution of fuzz to the aerodynamic drag of a tennis ball. As the velocity of the airflow past the ball is increased, fuzz fibres change from an upright position to a more horizontal one, reducing the drag contribution of the fuzz, and shrinking the projected ball area, at higher Reynolds values. Testing revealed differences in fibre orientation in two similar balls due to fabric dye.

A digital high speed camera captured frames at 2000fps from 0-40ms\(^{-1}\) and 0-3000rpm. A tufted fuzz ball was used for analysis as this ball indicated the most noticeable force differences that could be attributed to fuzz orientation and length during testing. It should be noted that the spin orientation is equivalent to viewing a topspin shot from above, as depicted in Figure 7.11.

![Spin orientation](Figure 7.11: Spin orientation for high speed video footage. Equivalent to viewing a topspin shot from above.)

The DFM was used to assess the effect of changes in wind speed and spin rates on ball fuzz orientation. Figure 7.12 shows the results of ball fuzziness for the speeds and spin rates shown in Figure 7.13. These results indicate that lower wind speeds and higher spin rates create increased roughness on the ball surface. While this analysis provides good qualitative information, it will not be directly compared to previous DFM results as image resolution and lighting were not suited to producing the experimental conditions required by the metric. Methods to assess changes in fuzz orientation and airflow during aerodynamic testing are further discussed in Chapter 11.

In addition to overall ball fuzziness, individual sections of the ball were also analysed to determine how the magnitude and location of ball fuzziness changed during testing. Figure 7.14 shows the results of this processing, with darker colours reflecting regions of increased ball roughness. The bottom section of the ball was not analysed due to the protruding support rod, though both ball halves should be symmetrical with respect to the horizontal axis in the images.

Several general conclusions can be drawn from an analysis of this high speed footage. Higher spin rates increase the amount of fuzz protruding from the ball’s surface, though this is more noticeable without airflow around the ball. Increasing wind speeds cause the fuzz on the front and top sections of the ball to
lie down. Lower spin rates allow the airflow to more easily flatten the fuzz to the ball's surface as there are smaller forces acting to lift the fuzz from the surface. These trends are reinforced by the increased drag coefficients at higher spin ratios. A higher spin ratio indicates increased spin and lower wind speeds, so the ball will have a rougher surface, creating increased drag forces.

### 7.5 Trajectory Model Development

To evaluate the importance of ball flight differences in the modern game, a trajectory simulator was developed using experimental data gathered in this chapter. While similar techniques have been used in previous research, they have been limited to non-spinning conditions (Haake et al., 2000a), ignored spin decay during flight, and assumed constant drag and spin forces throughout the trajectory (Goodwill & Haake, 2004a). The developed model incorporates spin decay and instantaneous drag and spin forces calculated from the ball’s spin ratio and Reynolds numbers during flight.

Spin is central to ball placement and control in tennis so it is necessary to incorporate it into any trajectory model looking to simulate strokes in tennis. Additionally, a given spin rate will change throughout a shot due to skin friction on the ball surface during flight and bounce conditions. Chakraverty et al. (2001) develop an iterative calculation for spin rate decay given by the ratio of skin friction from the rotational velocity of the ball to the moment of inertia of the ball. This is given in Equation 7.1 and was incorporated into the trajectory model to more realistically predict ball flight properties.

$$
\omega_{i+1} = \omega_i - \omega_i^2 \frac{R_D A S^2 C_D \Delta t}{360m}
$$

Varying drag and lift forces were calculated by fitting a three-dimensional third order polynomial surface to experimental data, shown in Figure 7.15. This allowed instantaneous drag and lift forces to be calculated at a range of spin rates and air speeds during trajectory computation.

Initial positional, rotation, and velocity information is given in Table 7.3 for a typical groundstroke and flat serve. Ball mass was held constant for samples as it was only used in the computation of the downward gravitational force. Computations were performed using Euler’s numerical method. As only topspin shots were considered, ball lift forces were directed downwards. The direction of ball drag force was determined using the ball velocity vector.

Post-bounce ball velocities were calculated according to the data collected by Pallis (1999a) for groundstrokes on an acrylic hard court surface. Rebound data was collected for flat, low, medium, and high topspin shots. Vertical and horizontal COR values calculated from this data are shown in Table 7.4. Data indicates increased topspin lowers the outbound ball angle and increases post-bounce ball velocity. This
Figure 7.13: Selected images from high speed footage of a very fuzzy ball.
Figure 7.14: Location of ball fuzziness for the top half of the ball through a range of air speeds and spin rates.
bounce approximation is seen as an improvement on the single COR value used by Haake \textit{et al.} (2000a) as it includes the effects of spin on ball velocity calculations. Because Goodwill \& Haake (2004a) assume spin remains constant throughout the trajectory and Haake \textit{et al.} (2000a) ignore spin, a method for calculating post-bounce spin was also required.

Three bounce conditions were identified in the current literature. The first model assumes the ball slides throughout impact when inbound at angles less than 16°. This model is used when assessing court surface pace ratings (ITF, 2006c). For inbound angles fitting this condition, post-bounce ball spin was reduced according to the motion of the ball. Brody (1984) assumes larger angles of incidence cause the ball to roll during impact. The increase in ball spin is the impulsive torque divided by the ball’s moment of inertia, assuming the ball does not deform on impact. Cross (2002a) also develops an impact condition where the ball ‘bites’, or grips the surface, during impact and rebounds with more spin than possible with rolling. Due the lack of experimental information regarding this final model and what causes this condition to occur in tennis balls, it is not considered in this application and balls were assumed to roll during impact at large angles.

Spin decay and the effect of the ball bounce on spin values is shown in Figure 7.16 for crosscourt forehand shots. While the rolling model does not show the same increases in ball spin experimentally observed by Pallis (1998a), it is an improvement over previous attempts. Differences could be possible due to the ball ‘biting’ the surface and producing higher spin rates.

Trajectory simulations for a new ball showed good agreement with previous models, though the use of experimental data, spin decay, and a bounce model, did create some differences. Figure 7.17 shows
Fig. 7.16: Spin decay during flight, with changes to ball spin during court impact.

Table 7.5: Time to baseline and bounce locations for simulated strokes.

<table>
<thead>
<tr>
<th>Serve</th>
<th>t (s)</th>
<th>x (m)</th>
<th>y (m)</th>
<th>Groundstroke</th>
<th>t (s)</th>
<th>x (m)</th>
<th>y (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bald</td>
<td>0.575</td>
<td>17.90</td>
<td>4.65</td>
<td>New</td>
<td>0.968</td>
<td>22.95</td>
<td>6.57</td>
</tr>
<tr>
<td>New</td>
<td>0.582</td>
<td>17.92</td>
<td>4.64</td>
<td>Loose</td>
<td>0.969</td>
<td>22.92</td>
<td>6.57</td>
</tr>
<tr>
<td>Loose</td>
<td>0.585</td>
<td>17.81</td>
<td>4.65</td>
<td>0.970</td>
<td>22.84</td>
<td>6.55</td>
<td></td>
</tr>
<tr>
<td>Tufted</td>
<td>0.588</td>
<td>17.80</td>
<td>4.65</td>
<td></td>
<td>0.972</td>
<td>21.76</td>
<td>6.52</td>
</tr>
</tbody>
</table>

Fig. 7.17: Trajectory analysis for two shot types using experimental data.
ball trajectories for a flat serve and cross court forehand, with times to the opposite baseline and bounce locations indicated in Table 7.5. The serve times are noticeably quicker than those reported by Goodwill & Haake (2004a). This could be due to the high reference forces found for the spinning sting, which could create lower than expected net drag forces on the ball and quicker flight times. Goodwill & Haake (2004a) also find that a worn ball travels up to 750mm further than a new ball during a serve. Analysis performed in this instance finds a maximum difference of 336mm between the bald ball and tufted fuzz ball.

While minimal differences in bounce locations and the time to baseline between ball types are found using this trajectory model, an examination of varied spin rates for a new ball produces larger positional differences. Figure 7.18 and Table 7.6 show the effects of varying spin rates on ball impact locations and times to opposing baselines for a crosscourt forehand. These results suggest that differences in ball spin may have a more significant effect on ball flight than the condition of the ball’s covering.

![Figure 7.18: Effect of increased spin on new ball placement.](image)

<table>
<thead>
<tr>
<th>Spin (rpm)</th>
<th>t (s)</th>
<th>x (m)</th>
<th>y (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.981</td>
<td>22.39</td>
<td>6.70</td>
</tr>
<tr>
<td>1000</td>
<td>0.964</td>
<td>22.15</td>
<td>6.63</td>
</tr>
<tr>
<td>2000</td>
<td>0.969</td>
<td>21.92</td>
<td>6.57</td>
</tr>
<tr>
<td>3000</td>
<td>0.952</td>
<td>21.67</td>
<td>6.50</td>
</tr>
</tbody>
</table>

### 7.6 Inclusion of Ball Impact Properties

While the trajectory model accounts for aerodynamic differences between balls, initial ball launch and bounce values remained unchanged. Impact data collected in Chapter 6 was used to develop simulations more representative of trajectory differences occurring during play. Adjustments to the trajectory model were made for each of the balls used in player testing performed in Chapter 9.

Racket rebound properties, including spin and COR, were used to adjust the initial launch velocities and spin imparted to balls. Differences in ball spin were only adjusted for the simulated groundstroke as the serve simulation was for a flat service. Court surface impact properties were altered using the rigid plate COR values. It is acknowledged that alternative testing, such as oblique court surface impacts, could provide a more accurate indication of differences in ball rebound speed and spin. COR values gathered from the service speed were used to adjust the horizontal COR, as the horizontal component of the ball velocity is much greater than the vertical component during court impacts, while the lower testing speed was used to adjust the vertical COR. Table 7.7 shows the differences in model parameters as compared to a new ball. Trajectories for each of the shots in the two studies are shown in Figure 7.19. Differences in time to the baseline and court impact locations are listed in Table 7.8.
Figure 7.19: Ball trajectories for balls used in player testing.
Table 7.7: Percent differences in ball samples as compared to a new ball.

<table>
<thead>
<tr>
<th>Racket COR</th>
<th>Spin</th>
<th>$\varepsilon_x$</th>
<th>$\varepsilon_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehand</td>
<td>Serve</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 week</td>
<td>3.3</td>
<td>-2.4</td>
<td>-17.9</td>
</tr>
<tr>
<td>3 weeks</td>
<td>5.4</td>
<td>0.1</td>
<td>-10.5</td>
</tr>
<tr>
<td>3 months</td>
<td>3.8</td>
<td>-3.3</td>
<td>-11.0</td>
</tr>
<tr>
<td>Bald</td>
<td>3.0</td>
<td>1.0</td>
<td>-5.6</td>
</tr>
<tr>
<td>Fuzzy</td>
<td>-1.8</td>
<td>-2.4</td>
<td>-1.9</td>
</tr>
<tr>
<td>Very Fuzzy</td>
<td>3.0</td>
<td>-3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 7.8: Court impact locations and time to baseline for trajectory simulations.

<table>
<thead>
<tr>
<th>Serve</th>
<th>Groundstroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>t (s)</td>
<td>x (m)</td>
</tr>
<tr>
<td>New</td>
<td>0.585</td>
</tr>
<tr>
<td>1 week</td>
<td>0.597</td>
</tr>
<tr>
<td>3 weeks</td>
<td>0.578</td>
</tr>
<tr>
<td>3 months</td>
<td>0.603</td>
</tr>
<tr>
<td>Bald</td>
<td>0.563</td>
</tr>
<tr>
<td>Fuzzy</td>
<td>0.589</td>
</tr>
<tr>
<td>Very Fuzzy</td>
<td>0.602</td>
</tr>
</tbody>
</table>

Figure 7.19 shows that altering initial conditions and bounce characteristics for the balls creates noticeably more variation in impact locations and flight times than those observed when only aerodynamic differences were considered in Figure 7.17. While aerodynamic differences in Chapter 7.5 altered flight times to the opposing baseline and impact locations by a maximum of 0.013s and 20cm, the addition of racket and court interactions created differences up to 0.10s and several metres. The largest variations for both groups of balls occurred with the forehand. As both shots had the same court impact conditions and testing produced similar racket COR differences at both testing speeds, differences in ball flight are attributed to ball spin variations present in the forehand simulation but not in the serve. Figure 7.18 indicates similar variations in ball flight when spin parameters were modified. Figures 7.19(a) and 7.19(c) clearly show the importance of varied initial ball spin created during the racket interaction.

It is hypothesised that the racket interaction and spin generation play a more significant role in overall ball performance than ball aerodynamics. Player testing conducted in Section 9.5, however, indicates players struggle to assess the controllability of ball spin during forehand and service shots. As it is unlikely players attribute all feel and performance differences directly to the racket impact, optimising this interaction could improve overall perceptions of ball feel and performance. Promising areas of future work and simulation to develop more accurate predictions of ball performance during play are more fully discussed in Chapter 11.

7.7 Concluding Comments

Work performed in this chapter provides both quantitative and qualitative information regarding tennis ball flight and the influence of surface condition. Important results are summarised below:

- Static drag force measurements show good agreement with the DFM and similarities to previous work.
- Spin does not indicate differences in the lift force generated by balls and eliminates drag differences between new and loose fuzz found during static testing.
- An improved trajectory model was developed incorporating spin decay, instantaneous calculations of drag and lift forces using a polynomial surface fit to experimental data, and altered initial launch and bounce properties.
• Trajectory analysis suggests differences in applied spin and the racket interaction could produce greater flight differences than those found between fuzzy and bald balls.
• High speed video footage used in combination with the DFM indicate that lower wind speeds and higher spin rates, or larger spin ratios, create increased roughness on the ball surface.
Chapter 8

Player Perception: Aesthetics

Quick visual assessments are one method players use to determine potential differences in ball performance when selecting a ball for service. This chapter investigates information players gather from aesthetic assessments of ball condition. Desirable aesthetics can make products 'more usable' and 'more sellable' to consumers. This increase in product appeal and customer satisfaction, through more or improved features, contributes to a strong brand identity, better product differentiation, and improved market share or price premium (Ulrich & Eppinger, 2004). The importance of appearance is described by Ashford (1969):

> The physical qualities of objects may be perfectly adequate and there may be no rational reason for our not being happy with them, but because of this irrational factor in perception we are completely satisfied only when the object's visual presence is consistent with purpose, function and material. In short, as much attention must be paid to an object's visual presence as is paid to any other consideration in making it; if it is not, there might be little point in having bothered to make it.

Most tennis balls appear similar when new, differing perhaps only in branding and felt type. Degradation, however, creates differences between balls and elicits varied attitudes from players concerning play properties and ball quality. This chapter details two sensory evaluation studies developed to identify important aesthetic attributes in tennis balls. The first study utilised two sets of tennis balls in a scoping investigation to identify key ball attributes. The second study used conjoint analysis to determine the relative importance and player perception of the three most important ball attributes.

8.1 Scoping Investigation

A relationship between appearance and wear emerged from Davies’ (2005) investigation into ball feel, suggesting visual indicators of degradation affect player perception of ball characteristics. Attributes including size, sphericity, cloth, visibility, and seam size were identified as important dimensions of ball appearance along with psychological influences such as branding and perceived quality. To evaluate these attributes with respect to ball degradation, ball preference and fuzziness rankings were elicited from players at several professional tournaments throughout Great Britain. When combined with follow up questioning, important aesthetic attributes in tennis balls could be established.

Several sensory evaluation metrics were discussed in Chapter 2. Promising techniques include rating and ranking the ball samples. While ratings assess magnitude differences between samples, training would be required to ensure scaling was appropriately applied to ball attributes. Ranking provides data on ball differences and minimises panel training and evaluation time. Paired comparisons, a subset of ranking methods, allow for easy identification of subtle differences. A sample of ten, however, results in 45 different pairs to be evaluated, proving time consuming and monotonous for test subjects. Using multi-paired and grouped ranking tests allows greater numbers of comparisons to be made more quickly, with similar
statistical significance. When panellists are familiar with the attribute in question, ranking tests can be performed quickly with little training (Meilgaard et al., 1999).

Pilot testing evaluated two balanced partial blocks and one complete block to determine the method most suited to testing conditions. While partial blocks were preferred by panellists, a complete replication was time consuming and impractical as time and complexity are important considerations for a maximum response rate. As similar statistical results were produced with both methods, the complete block design was determined the most suitable method to implement with players.

8.1.1 Trials

Two trials were developed to investigate the role of aesthetic attributes in tennis balls. Trial 1 was used to scope attributes important in visual assessments using balls from leading manufacturers in varied states of degradation. Samples are shown in Figure 8.1. Trial 2 was used to address the outcomes of Trial 1 and evaluate more specific areas of ball appearance. Pressureless, unmarked samples, shown in Figure 8.2, were used with a range of surface conditions to eliminate differences in pressure, ball brand and logo, and colour differences. To develop these samples without noticeably changing the colour of the ball felt, several methods of modification were used on the balls. Samples were play tested on a clean, indoor court, rubbed vigorously against racket strings, fired in laboratory ball cannon equipment, shaved to varying degrees with an electric razor, and washed and dried to simulate play in wet conditions. Pilot testing established ten balls as both a manageable sample size and suitable range of ball conditions for testing.

Two rankings were performed in each trial. The first assessment ranked samples with regards to preference for match play from best to worst, evaluating attributes important to players when choosing balls for play. This ranking looked to identify attributes important in the overall quality and playability of the ball. Players were informed of the criteria for the second ranking, ball fuzziness, only after the first ranking was completed. This was done so that preference would be determined only by instinctive player determinations and not influenced by thoughts of ‘fuzziness’ or other ball characteristics introduced by the investigator. Players were allowed to handle balls, but not to bounce them. This confined the sensory evaluation to visual and tactile attributes. All testing procedures were approved by the University Ethics Committee.

Panellists also stated whether they felt each ball was acceptable for match play. These acceptability ratings provided an acceptance percentage for each ball and will be examined as an alternative to preference rankings in future work. Several open-ended, follow up questions were asked of players after the rankings were performed. Examples of these are listed below, with questionnaires provided in Appendix F.

- Why did you feel ball x was the best (worst) for play?
- What characteristics did you look for when ranking the balls?
- What performance properties do you determine from the appearance of a ball?

8.1.2 Players

Meilgaard et al. (1999) suggest a minimum of eight subjects in sensory evaluations, with discrimination much improved with over sixteen subjects. Thirty-nine competitive male and twenty-eight competitive female tennis players were gathered from several ITF professional tournaments around Great Britain, averaging 14 years playing experience with an average male international ranking of 460 and an average female international ranking of 848.

Verbal and written instructions were provided to all participants and clarification offered during testing if needed. No method was developed for removing unsuitable data from future analysis. As there was no ‘right’ answer concerning perceived fuzziness or ball preference, suitable assistance and feedback during testing was seen as a way to ensure participant reliability.
Figure 8.1: Set of balls used in Trial 1.

Figure 8.2: Set of balls used in Trial 2.
8.1.3 Data Analysis

More detailed information on the analysis of complete block rank data is given in Appendix C. Rankings determined to be significant according to the $\chi^2$ distribution are analysed using Fisher’s Least Significant Difference (LSD), given in Equation 8.1, to determine individual differences between ball samples (Meilgaard et al., 1999).

The Kendall coefficient of concordance, $W$, determines the similarity between several sets of rankings according to Equation 8.2 (Siegel & Castellan, 1988). Agreement in rankings is important to ensure the ranking criteria is relevant to the balls under investigation. The coefficient of concordance ranges from 0 to 1, with higher values indicating that the panelists are ranking the objects on similar standards. Lower values could also suggest panelists had trouble differentiating samples.

$$
LSD = t_{\alpha/2,\infty} \sqrt{\frac{Nn(n+1)}{6}}
$$

$$
W = \sum_{j=1}^{n} (\bar{R}_j - \bar{R})
$$

8.2 Results

Ranking results are discussed in this section along with important ball characteristics identified by participants. The range of ball conditions in Trial 1 made it more effective in identifying important attributes in ball appearance, though the balls in Trial 2 showed better agreement with the digital fuzziness metric.

8.2.1 Trial 1

Both panellist rankings shown in Figure 8.3 are significant according to the $\chi^2$ distribution. The range of statistical equivalence for the samples, given by Fisher’s LSD, is shown in Figure 8.3 by the tolerance bars shown above each point or group of adjacent points. Balls separated by distances larger than these bars have significantly different rank sums.

The new ball was unanimously preferred by all players and Ball 4, a particularly worn, bald, discoloured ball was least preferred by all but one participant (and ranked baldest by all participants). Although other balls varied in their rankings, the coefficient of concordance ($W = 0.846$) indicates good agreement among panelists in determining ball preference.

![Preference and Fuzziness Rankings](image)

Figure 8.3: Ranking results for Trial 1.

Fuzz rankings showed similar agreement by players ($W = 0.873$), though variations in how players perceive fuzziness may have prevented stronger agreement. Some players may find tufted fuzz balls fuzzier than balls with long stringy fibres, and vice versa. Groupings from Figure 8.3(b) suggest four surface conditions similar to those previously identified in Chapters 2 and 3: tufted fuzz, loose fuzz, new, and bald.

Both the preference and fuzz rankings suggest groupings of balls identified by players. Balls 5, 6, and 10 are clustered in both the preference and fuzz rankings, suggesting they are similar in condition. This is
interesting because Ball 5's colour was noticeably brighter than that of Balls 6 and 10, perhaps indicating that colour is of secondary importance when determining player perceptions. Balls 2 and 7, both logoed balls with loose fuzz, were also similar in both rankings.

Players indicated ball brand, logo clarity, brightness, colour, size and shape, and 'newness' of the ball were important in preference rankings. Ball seams were not mentioned as a factor in player evaluations. From these responses, three main areas, in addition to ball fuzziness, were judged important in determining ball preference: ball brand and logo, colour, and size. As not all of these attributes are directly related to ball performance, player opinions likely result from past playing experiences with balls having similar attributes. Although players stated these influences did not influence their fuzziness rankings, Trial 2 aimed to isolate ball fuzziness and form more solid conclusions concerning the relationship between fuzziness and player perception.

8.2.2 Trial 2

As tufted fuzz balls were clearly ranked fuzzier in Trial 1, this trial looked to determine significant differences between new and loose fuzz balls. Balls in Trial 2 were processed to incorporate loose fuzz through to bald balls. All balls were of uniform colour, internal pressure, and unmarked to eliminate some attributes players used in Trial 1 to determine ball preference.

Both rankings, shown in Figure 8.4, were significant according to the \( \chi^2 \) distribution. Ball 5, a very bald ball, was ranked least preferred for play and baldest by all participants. Ball 10 was ranked second baldest by 75% of panellists. The new ball was most preferred by 28.1% of players, compared with the 100% preference for the new ball shown in Trial 1. Preference rankings showed less agreement (\( W = 0.596 \)) than Trial 1, likely because the balls were of uniform colour, manufacture, pressure, and free of logos on the ball surface. Similar agreement was found, however, for the fuzz rankings (\( W = 0.865 \)). With the omission of tufted fuzz balls, this trial produced five balls ranked balder than a new ball, compared to just three in Trial 1. This indicates that players may perceive two levels of baldness, in addition to two levels of fuzziness indicated in Trial 1.

![Figure 8.4: Ranking results for Trial 2.](image)

Figure 8.5 shows Trial 2 has better agreement with the DFM developed in Chapter 3. Differences are attributed to the role of additional aesthetic attributes in Trial 1 that could have affected perception of ball fuzziness. Players participating in Trial 2 mentioned attributes such as fuzziness, colour, and ball size as important in preference rankings. It is surprising that ball colour was mentioned as the balls were of consistent colour and manufacture. Perceived differences in ball size are attributed to the role of cloth in perceived ball size.

8.3 Discussion

Player responses to aesthetic ball attributes identified several areas of perceived performance differences: ball flight, control, stiffness, and weight. These perceived performance differences emphasise the importance of aesthetics in product differentiation and perceived product quality with respect to tennis balls.
8.3.1 Ball Flight and Control

Results suggest that ball fuzziness plays an important role both in perceived ball aerodynamics as well as in player perception of the ball-racket interaction. A certain amount of fuzz may be necessary to provide players with a feeling of control over the ball. Seventy-two percent of players commented on the importance of ball flight speed with respect to ball fuzziness, including 30% who also felt ball spin and control were affected by ball condition. Bald balls were perceived to travel quickly and react poorly to spin, making them harder to control and more difficult to place. Other players mentioned that their ball preference was dependent on the match situation and point to be played, as they would choose different balls for a first and second service.

The relationship between the fuzziness and preference rankings are shown in Figure 8.6. Figure 8.7 shows a similar relationship using the acceptability ratings also gathered for the samples. A second order fit for the trial data was chosen as the rankings indicated that extremely fuzzy and bald samples were consistently rejected, while newer samples were generally accepted. Both Figures 8.6 and 8.7 indicate that new tennis balls, and those with aesthetics similar to new balls, are more widely accepted and have higher preference ranks by players. Both evaluations show a weaker correlation with Trial 1 data. The same two balls in Trial 1 appear as noticeable outliers in both relationships. This is attributed to colour and branding differences on the balls that influenced player rankings. The unmarked samples in Trial 2 show a better fit as the cloth condition was the only difference between the balls. These results suggest that colour and the clarity of the ball logo can influence player preferences. This is attributed to previous experience players have with discoloured balls and those lacking logos, causing them to rate these samples poorly.

The similarity in Figures 8.6 and 8.7 suggests good agreement between the acceptability ratings and preference rankings from both Trials. The Spearman rank order correlation coefficient indicates significance ($\alpha \leq 0.001$, $r_s = 0.915$ and 0.988), suggesting that a simple dichotomous question concerning ball acceptability for play may be able to replace preference rankings with a sufficient number of panellists.

8.3.2 Stiffness and Weight

Players were instructed to classify balls solely on appearance with regards to fuzziness and preference for play. While handling the samples, many players instinctively squeezed the samples to judge the pressure of the balls. Large percentages of players indicated that differences in ball appearance altered ball stiffness (37% of respondents) and weight (40% of respondents). Even when reminded that internal pressure was not a factor, these reactions suggest that aesthetics cannot be entirely separated from other ball characteristics.
Some players in Trial 2 continued to indicate pressure differences in the balls, even though the internal pressure and rubber core for each of the balls remained the same.

Players also remarked that fuzzy balls felt heavier and had to be hit harder. Weber's fraction for a lifted weight is 0.20, making a 1.2g difference in ball mass the threshold for 'just noticeable difference' (Coren et al., 2004). While some players may have identified increased mass in some of the samples, mass differences do not strictly correlate with surface condition as new balls will generally be heavier than both fuzzy and bald balls. 'Heaviness' identified by players is more likely related to the feeling that fuzzier balls must be hit harder due to increased aerodynamic drag forces. Bald balls were also assumed to be older and therefore 'react' less off the court surface.

### 8.4 Role of Ball Attributes in Ball Playability

Several attributes were identified during the scoping investigation of ball aesthetics: ball fuzziness, branding, logo clarity, brightness and colour, size and shape, and the 'newness' of the ball. These characteristics can be grouped into three main areas for a more focused analysis: colour, fuzziness (including size and
shape differences), and branding and logo. To evaluate the relative importance of these attributes in decision making, a follow up study was designed incorporating ball preference and selection decisions. Two methods were considered for gathering this information (Jaeger et al., 2001):

**Conjoint analysis** Assumes choice behaviour is governed by a maximisation of preferences and products are composed of attributes from which users gain utility.

**Choice based analysis** Experiments produce data for discrete choice models, emphasising competitive context of products to forecast future choice behaviour. Data gathered through rank or single choice values.

Conjoint analysis was deemed more suitable for this application and determining the relative utilities of individual ball attributes identified for this study. An online conjoint study was developed to assess player attitudes towards ball 'playability' concerning the three main ball attributes: colour, fuzziness, and logo marking.

### 8.4.1 Conjoint Analysis

Conjoint analysis assesses the role of multiple product attributes on psychophysical judgements like preference and choice. It aids product development and can be used to make pricing and purchasing decisions (Gustafsson et al., 2001). By analysing decision making and tradeoffs, consumer preference and purchasing decisions can be better understood and catered for. Conjoint models assume that the set of objects is at least weakly ordered, can be represented by an additive utility model, and is interval scaled (Smith, 2006).

There are three main utility models used to assess preferences (Green et al., 2001):

- **Part-worth** Attribute utilities are represented by a piecewise linear curve. Curve formed by straight lines connecting point estimates.

- **Vector** A single linear function that assumes preference is directly proportional to attribute levels. Represented by a single linear variable.

- **Ideal point** A curvilinear function defines an optimum attribute level with decreased utility at levels above and below this point.

Internet based conjoint measurement has previously produced highly correlated aggregate and subgroup results, with similar segmentation to personally conducted investigations (Moskowitz et al., 2000). Dahan & Srinivasan (2000) perform an internet based study to evaluate new product concepts, using a fractional factorial design to limit the number of product profiles under consideration by respondents. Results indicate virtual product concept testing allows low-cost, quick generation of prototypes and rapid collection of consumer preference data, while providing similar results to those obtained with direct evaluations. Melles et al. (2000) suggest several precautions for investigations conducted over the internet with regards to data quality, assuming adequate response and good experimental design:

- Assess reliability and validity of results.
- Use incentives to encourage reliable responses.
- Encourage feedback from users.
- Precede aggregate analysis with individual data analysis to identify 'bad data'.

### 8.4.2 Experimental Design

Three independent variables were selected for analysis: colour, fuzz, and logo. Table 8.1 indicates attribute levels deemed appropriate for this investigation through previous work. Four fuzz conditions were selected for evaluation. These levels correspond to those identified in the development of the DFM in Chapter 3 and used in aerodynamic and impact testing. They include bald, new, fuzzy (loose fuzz), and very fuzzy (tufted fuzz) balls. Although two levels of perceived baldness were suggested from Trial 2 of the scoping
Table 8.1: Attribute levels determined for conjoint study.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Fuzz</th>
<th>Logo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dull</td>
<td>Bald</td>
<td>New</td>
</tr>
<tr>
<td>Bright</td>
<td>New</td>
<td>Most</td>
</tr>
<tr>
<td>Fuzzy</td>
<td>Partial</td>
<td></td>
</tr>
<tr>
<td>Very fuzzy</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

(a) Bright bald ball with partial logo. (b) Dull new ball with most of a logo. (c) Bright fuzzy ball with new logo. (d) Dull very fuzzy ball with no logo.

Figure 8.8: Examples of ball samples used in online survey.

investigation, the baldest balls were seen to be unfamiliar to experienced players. For this reason, they were not included in this analysis of ball playability. Four levels of logo condition were also identified through observing worn ball samples. These include a new logo, two partial logos, and an unmarked ball. Only two colour levels were selected as the previous study indicated that this may only be a secondary influence in determining ball preference. Examples of these attributes are shown in Figure 8.8.

Factorial designs are used when more than two independent variables are associated with an experiment. A full factorial design combines each setting of every factor with each setting of every other factor. For this investigation, with two colour levels, four fuzz levels, and four logos (a 2x4x4 design), 32 ball profiles would need to be evaluated by each panelist to determine individual attribute utilities. Fractional factorial designs allow only a portion of these profiles to be evaluated, but still maintain the ability to determine individual utility values (Dean & Voss, 1999).

While main effects can be estimated with fractional designs, confounded and higher order effects are more difficult to determine. As this is the first structured investigation into these attributes, results can be used to structure future studies into the importance of higher order effects if deemed necessary. The fractional factorial design shown in Table 8.2 was determined through the use of orthogonal arrays and develops sixteen samples for analysis. All sixteen ball images used in the design are shown in Appendix D.

8.4.3 Web Site Development

A complete block ranking was unsuitable for all 16 samples due to the limited screen size associated with web implementation. A partial block arrangement would require evaluation of all 20 blocks (using blocks of four balls) to calculate individual utility values due to the fractional design. The length of time required for survey completion was important to maximise response rate, so an alternative method to ranking was pursued. Ratings provide interval data for each sample and also indicate a magnitude of difference between samples. A semantic differential scale, shown in Figure 8.9, with descriptive endpoints was used to assess ball preferences. The psychological meaning of the scale will rely on past playing experiences and situations affecting participating players (Osgood et al., 1967). Individuals using the scale will each have unique reference points concerning ball condition and use different portions of the scale.

Least playable   | Most playable

Figure 8.9: Rating scale used in survey.
Table 8.2: Description of samples used in online survey.

<table>
<thead>
<tr>
<th>Ball</th>
<th>Colour</th>
<th>Fuzz Level</th>
<th>Logo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dull</td>
<td>Very fuzzy</td>
<td>Most</td>
</tr>
<tr>
<td>2</td>
<td>Bright</td>
<td>New</td>
<td>Most</td>
</tr>
<tr>
<td>3</td>
<td>Dull</td>
<td>Very fuzzy</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>Bright</td>
<td>Bald</td>
<td>Partial</td>
</tr>
<tr>
<td>5</td>
<td>Dull</td>
<td>Fuzzy</td>
<td>Partial</td>
</tr>
<tr>
<td>6</td>
<td>Bright</td>
<td>Very fuzzy</td>
<td>New</td>
</tr>
<tr>
<td>7</td>
<td>Bright</td>
<td>Bald</td>
<td>New</td>
</tr>
<tr>
<td>8</td>
<td>Dull</td>
<td>New</td>
<td>New</td>
</tr>
<tr>
<td>9</td>
<td>Bright</td>
<td>Very fuzzy</td>
<td>Partial</td>
</tr>
<tr>
<td>10</td>
<td>Dull</td>
<td>Fuzzy</td>
<td>New</td>
</tr>
<tr>
<td>11</td>
<td>Bright</td>
<td>New</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>Bright</td>
<td>Fuzzy</td>
<td>None</td>
</tr>
<tr>
<td>13</td>
<td>Dull</td>
<td>Bald</td>
<td>Most</td>
</tr>
<tr>
<td>14</td>
<td>Dull</td>
<td>New</td>
<td>Partial</td>
</tr>
<tr>
<td>15</td>
<td>Dull</td>
<td>Bald</td>
<td>None</td>
</tr>
<tr>
<td>16</td>
<td>Bright</td>
<td>Fuzzy</td>
<td>Most</td>
</tr>
</tbody>
</table>

Meilgaard et al. (1999) recommend using a 10 to 15 point scale. For this application, an odd numbered scale was selected to give subjects a neutral middle value. A nine point scale was determined to give panellists a suitable range and level of detail for responses and has also been used in previous psychometric investigations of sports equipment (Roberts, 2002).

Pilot testing indicated appropriate page loading times and browser and platform independence. Wordings and instructions were refined through trials and interviews to improve understanding by participants. While the survey looked to determine ball preference ratings, it was found that ‘most’ and ‘least’ preferred were confusing terms on the semantic differential scale. ‘Most playable’ and ‘least playable’ were determined to be more suitable phrases.

Participants were shown an example of the rating scale along with a standard new ball on the introductory page of the survey to familiarise themselves with the evaluation procedure and determine a reference level for future ratings. Any variations in this reference level during early testing was minimised by randomising ball presentation for all participants. High playability was described as a combination of preference and suitability for match play.

As the initial study was conducted within Great Britain, this follow up study was targeted at a similar tennis population. Over 600 tennis clubs in Great Britain were emailed a link to the survey, and asked to forward the survey to their members. Information such as playing and coaching standard, experience, and frequency of play were collected from all panellists.

To abet reliable responses, opinions on survey design and ball conditions were welcomed and participants offered a copy of results once available. The survey utilised a simple, functional methodology and was presented to users as a way to improve current ball designs. Quick loading pages and a minimal time commitment were emphasised to improve user response. A JavaScript function was written to require ratings for each sample and ball presentation was randomised through use of a PHP script.

8.5 Data Analysis

Two main areas of data analysis were pursued. The first step involves assessing the reliability and validity of collected data. Once this is determined, individual attribute utilities can be calculated and responses segmented into preference groups.
8.5.1 Reliability and Validity

Reliability relates to the measurement error associated with responses that affects the internal consistency of tests. Reliability limits test validity, but does not guarantee it. Cronbach’s alpha ($\alpha_c$) provides reliability estimates based on the ratio of the estimated true variance to the observed variance. It is an important component of the domain-sampling theory of measurement error (Hays, 1988; Nunnally & Bernstein, 1994). Further details are located in Appendix C.

Nunnally & Bernstein (1994) detail three components of validity: construct, predictive, and content. Construct validity evaluates if a test measures what it is supposed to measure according to an external criterion. Content validity assesses if a scale directly measures what it is designed to measure. The ITF standardised test limits are available for determining physical limitations in ball playability, but no guidelines relating to perceived playability exist. Predictive validity is most relevant in this investigation, as it involves the ability to predict future behaviour outside of scale usage. Validity will be determined by goodness-of-fit ($R^2$) between conjoint models and individual ratings.

Individual responses with $R^2$ values below 0.60 will be deemed unsuitable for aggregate analysis. As there was no individual interaction or clarification available to participants during the survey, this is seen as a suitable lower acceptance limit. Rejected data indicates a subject did not consistently use any of the three attributes in rating samples or perhaps changed their point of reference during testing.

8.5.2 Attribute Utility and Segmentation

Two methods for determining attribute utilities and segmentation were examined. The first method involves using an ordinary least squares (OLS) multiple regression to determine attribute part-worth values (Louviere, 1988). Equation 8.3 shows the relationship used to determine part-worth values, with utilities determined from the coefficients ($\beta_i$). Dummy variables ($z_i$) for each level of the three attributes are used to code the equation for use with ratings ($y$) for the ball samples. Individual part-worth values are then segmented using a clustering method, typically k-means, a partition algorithm. Clusters according to the k-means method are determined by minimising any of several metrics: the maximum distance between a centroid and any object, the sum of the average distance, the sum of variance, or total distance between all objects and their centroids. Objects are initially randomly assigned to a cluster and then reassigned according to a global optimisation method and the minimisation metric (Everitt et al., 2001).

$$y = \beta_0 + \beta_1 z_1 + \beta_2 z_2 + \beta_3 z_3 + \beta_4 z_4 + \beta_5 z_5 + \beta_6 z_6 + \beta_7 z_7 + \beta_8 z_8 + \beta_9 z_9 + \beta_{10} z_{10}$$

Equation 8.3

A second method determines aggregate utility functions for clusters instead of individual values (Desarbo et al., 1991; Kamakura, 1988). While this method is seen to be useful in fractional factorial designs where some data relationships are not directly evaluated, there is no analysis of data on the individual level. By analysing model fit to individual data sets, responses not suited to a linear utility function can be removed from analysis.

A limitation of the k-means clustering method is that the number of clusters must be predetermined during analysis. Because of this, it can be difficult to determine ‘natural groupings’ that emerge from the data. Several methods have been developed to optimise the number of clusters in a k-means analysis (Tibshirani et al., 2001). A well recognised method is the silhouette statistic proposed by Kaufman & Rousseeuw (1990). The authors propose maximising the statistic over the data set to indicate good separation in cluster groupings. Further detail is given in Appendix C.

8.6 Results and Discussion

One hundred and seventy nine responses were received for the survey. All players reported playing on a daily or weekly basis and included average club players, county representatives, and former professional players. Many also had coaching qualifications or experience at the club level. Participants averaged 21.18
(σ = 12.73) years playing experience. Roberts (2002) details a procedure used by Giuliano & Ugo (1992) to normalise ratings for each participant. This adjusts for users having differing standards of reference for rating scales. Performing this step adjusted the coefficients for the regression model, but not the goodness-of-fit. As only the locations of the maximal part worths were desired, and not their magnitude, ratings were not normalised. Average ratings, with one standard error, are shown in Figure 8.10. The ratings were significant at the α = 0.05 level (p < 0.001). Average values for each ball type are shown in Table 8.3. The lower standard deviations present with the fuzzy and very fuzzy ball indicate more consensus concerning their poor playability. Ball fuzz differences produced the largest range of average ratings, though partial ball logos also served to lower ball playability.

![Figure 8.10: Average ball ratings shown with one standard error.](image)

<table>
<thead>
<tr>
<th>Table 8.3: Average ratings for ball attribute groups.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Colour</strong></td>
</tr>
<tr>
<td>Bright</td>
</tr>
<tr>
<td>Dull</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

*Note: standard deviations given in parentheses.*

Post-hoc analysis (Fisher’s LSD) indicated several significant differences between balls. Balls 1,3,6 and 9 were significantly less playable than the other balls in the analysis. These balls were all very fuzzy, though differed in colour and logo condition. Balls 5 and 16 were bright, fuzzy balls with partial logos that were rated more playable than the very fuzzy balls, but significantly less playable than all other samples. Balls 7 and 8, the bald and new balls with new logos, were rated significantly more playable than all other ball samples. These preliminary results indicate the importance of ball fuzziness and the ball logo in playability evaluations by players.

The data can be considered reliable as Cronbach’s alpha (αc = 0.815) for the data is above the 0.70 threshold suggested by Nunnally & Bernstein (1994). This statistic indicates that the playability scale produces repeatable results.

### 8.6.1 Determination of Utility Values

The average $R^2$ for all participants was 0.829. A value of 0.60 was determined appropriate for minimum cut off for suitable participants. Participants below this level may have have been unclear on rating
requirements or altered their point of reference during testing. This resulted in ten participants data being removed from further analysis, leaving 169 sets of data for further processing.

Each set of data was fit with an OLS multiple regression to determine utilities for the 10 variables in the analysis. These utilities were then fit with a curve according to the ideal point model to determine an maximum attribute utility. By using the maximum value of the curve across all attribute levels, two attribute levels producing similar utilities could be accounted for. The locations of maximum utility for each attribute were used in clustering responses. Figure 8.11 gives an example of utility curves for a subject's ratings. The locations of the maximum values of the curve was used to cluster responses.

The relative importance placed on each attribute by a participant can be determined from the difference in their maximum and minimum utility values. Figure 8.12 shows the relative importance values for all participants. Ball colour is noticeably less important than ball logo and fuzz. The average relative importance score, shown in Table 8.4, will be used to scale each axis so appropriate significance is given to each attribute during clustering. It should be noted that while overall differences in ball colour did not play a significant role in determining ball playability, isolated regions of discolouration due to impacts could be more noticeable to players and affect perceptions.

8.6.2 Clustering

The k-means algorithm minimised the sum of squared Euclidean distances over all objects and clusters. These distances are based on the locations of individual maximum utility values. The intermediate values

Figure 8.11: Utility curves for a set of ball ratings.

Figure 8.12: Relative importance values for ball attributes.
Table 8.4: Relative importance of ball attributes.

<table>
<thead>
<tr>
<th></th>
<th>Colour</th>
<th>Fuzz</th>
<th>Logo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.486 (0.402)</td>
<td>4.398 (1.504)</td>
<td>2.333 (1.005)</td>
</tr>
</tbody>
</table>

Note: standard deviations given in parentheses.

on the fuzz and logo axes were located according to the percentage of logo remaining on the ball or metric roughness value as compared to the two endpoints. Optimal clustering was determined by evaluating the silhouette statistic for clusters of \( k_c = 2 - 5 \). Five replicates were performed during clustering to avoid local minimums. Higher numbers of clusters decreased the silhouette statistic even further than observed with \( k_c = 5 \). Table 8.5 suggests an optimal grouping of four groups.

Table 8.5: Percentage of panellists assigned to clusters \( k_c = 2 - 5 \).

<table>
<thead>
<tr>
<th>( k_c = 2 ) (s = 0.786)</th>
<th>( k_c = 3 ) (s = 0.910)</th>
<th>( k_c = 4 ) (s = 0.938)</th>
<th>( k_c = 5 ) (s = 0.803)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 81.1</td>
<td>Group 3 18.3</td>
<td>Group 6 27.8</td>
<td>Group 10 16.0</td>
</tr>
<tr>
<td>Group 2 18.9</td>
<td>Group 4 52.7</td>
<td>Group 7 16.0</td>
<td>Group 11 18.3</td>
</tr>
<tr>
<td>Group 5 29.0</td>
<td>Group 8 3.6</td>
<td>Group 12 27.8</td>
<td>Group 13 34.3</td>
</tr>
<tr>
<td>Group 9 52.6</td>
<td>Group 10 16.0</td>
<td>Group 14 3.6</td>
<td>Group 12 27.8</td>
</tr>
</tbody>
</table>

Figure 8.13 shows results of clustering for \( k_c = 2 - 4 \). As there were only two colour levels, and preferences assigned to one of them, the three-dimensional space was split into two two-dimensional figures based on colour preference to improve visualisation. Initial group divisions were made based on logo preference, with 81.1% of panellists (Group 1) preferring a ball with fuzz ranging from bald to new, with a new logo. Further divisions were then made based on ball fuzziness with the four optimal groups shown in Figures 8.13(e) and 8.13(f). Group 9 indicates that 52.6% of panellists felt a new ball with a new logo and the highest playability. Surprisingly, an unmarked bald ball was the next largest group, with a bald ball and new logo third.

These results suggest that while the majority of participants found high playability with a ‘standard’ new ball, there is still a large group (43.8%) who prefer a balder ball. This suggests that manufacturing a ‘less fuzzy’ tennis ball may appeal to a relatively large segment of the tennis population. The low preferences for extremely bald balls indicated in the scoping investigation does suggest, however, a limit to ball baldness to capitalise on this appeal.

8.7 Concluding Comments

The investigation into ball aesthetics performed in this chapter produced a range of ball attributes important to players, as well as levels of differentiation between worn and fuzzy samples. Several important areas emerged from the work conducted in this chapter:

- Sensory evaluation techniques can be successfully used to elicit perception of product quality and preference. Acceptability ratings, when used with a sufficient number of panellists, can replace preference rankings.
- There exists an optimum range of fuzziness, surrounding the condition of a new ball, that players prefer. Ball aesthetic attributes affect player perception of ball flight, control, stiffness, and weight.
- Ball fuzziness is nearly twice as important as ball logo in determining ball playability, while colour can be considered only a secondary influence in determining playability.
- The majority of players prefer a new to bald ball with a new logo. A relatively large segment of the panellists indicated preference for a ball balder than a new ball, suggesting new directions in ball manufacturing.
The perceived differences and preferred attributes in ball playability should encourage manufacturers to find aesthetic points of product differentiation to improve perceived ball quality, degradation, and playability.
This chapter assesses player perception of tennis ball feel and performance for fuzzy and naturally aged tennis balls. These two areas of investigation were identified through previous work performed in Chapters 5-7 as major components of tennis ball degradation. While ball performance, and a player's ability to control this performance, is crucial to success on the court, feel has the ability to influence player opinions of this performance and affect attitudes towards ball conditions. Davies (2005) analyses feel in tennis ball impacts by focusing on ball impact sound and vibration during player testing. Ball types, however, were confined to new balls. It is hypothesised that ball degradation will play a significant role in influencing perceptions of feel and performance. This chapter details investigations performed to determine the influence of natural ball ageing and fuzziness in influencing player perceptions during play.

9.1 Test Development

The dynamic nature of tennis makes it difficult to stimulate appropriate 'match-like' feel and performance perceptions from players. A single point can involve a range of shots, ball speeds, spin rates, and player movements. The testing methodology aimed to capture this range of play properties while still allowing players the opportunity to assess and express these differences. It was determined that each testing session should last no more than one hour, to minimise player physical and sensory fatigue, and should incorporate more than one shot type. All testing procedures were approved by the University Ethics Committee.

Two shots were selected for use during testing: the serve and the forehand. The serve was incorporated as it is the only shot where players handle balls and it is hypothesised this can significantly affect player perceptions. Players were allowed to choose their preferred side of service and instructed to use the combination of first and second serves most suited to assessing ball differences. They were allowed several practice shots to determine these preferences. A cross-court forehand was also selected because it is a commonly used, high-percentage shot (due to the lower net height and the longer distance available on the court diagonal). Deep placement is used to limit an opponent’s return options and was therefore incorporated into the court setup and scoring system shown in Figures 9.1 and 9.2 (Holm, 1987). Balls for the forehand were delivered at 23ms⁻¹ using a BOLA ball machine. This testing speed is seen as an appropriate groundstroke speed for both the men’s and women’s game and Haake & Goodwill (1997) find average ball speeds of 23.1ms⁻¹ for medium paced forehands (Pallis, 1999b).

To examine a potential relationship between shot outcome and ball evaluations, a scoring system was developed to monitor the accuracy of player shots. Positive shot scores were given to shots landing within or around the target area for forehand shots or within the service box for serves. No score was given for shots landing out of play or noticeably short. Negative values were given for shots not clearing the net as elite players should not have any difficulties executing these shots within the given testing setup.
9.1.1 Paired Comparisons

Paired comparisons are useful for the detection of subtle subjective differences between objects as subjects must only recall their perceptions of the previous object. Subjects are not required to identify the magnitude of the difference, only the direction, making this technique particularly useful for participants inexperienced at subjective evaluations (David, 1988).

Davies (2005) uses paired comparisons to investigate sound and vibration differences in tennis balls. Each comparison was performed with six alternate impacts of two ball types. Pilot testing indicated that the three impacts used for each ball type was suitable for players to determine differences, though the impacts were grouped instead of alternated (e.g. three shots with ball A followed by three shots of ball B instead of alternating ball A with ball B). This allowed players to fully assess and form conclusions about the first sample before evaluating a second. A complete paired comparison design was used so each player evaluated all possible ball pairings. Because of this, four balls, and the resulting six pairs, were the limit of possible comparisons for both shot types in the desired time frame.

Players were monitored for sensory fatigue, though pilot testing and observations indicated the change in shot type midway through testing helped prevent this. As the test was relatively static and focused on perception and not shot outcome or extreme skill, physical fatigue did not play a role during testing. Players were offered a break between shots if desired.

To eliminate potential order effects during testing, the Latin Square design shown in Table 9.1 for balls A-D was used to order the presentation of the six comparisons. Players were presented with a different ordering for each shot and each replicate was used the same number of times. Additionally, the first ball of the pair presented to the subject was randomised. In all testing, the forehand shot was performed before
the serve to prevent players from handling the balls and pre-determining perceptions that would allow them to ‘guess’ the correct response during the forehand shot. As a result, these handling effects could be observed in comparison differences between the forehand and the serve.

An important detail in the testing methodology was that players were allowed to choose a ‘no difference’ option for a specific pairing. This is of note because although the players were all highly experienced, aesthetic attributes not under investigation were tightly controlled. This prevented players from associating ball characteristics that may occur together in uncontrolled situations (e.g. a discoloured, bald, flat ball with a worn logo). As Chapter 8 identifies the importance of ball aesthetics in tennis, the ‘no difference’ option was allowed as it was expected some players could struggle to identify differences without these attribute differences. The no difference option complicates the data analysis procedure discussed throughout this chapter. Several analysis steps were used with this data:

- Determine any influence of shot outcome on player scoring tendencies.
- Determine consistency of player responses and remove inconsistent players from future analysis.
- Identify agreement among subject responses.
- Fit responses with a linear model and determine a merit value for each ball and corresponding characteristic.
- Identify significant differences in feel and perception for ball samples.
- Examine player reliability between shot types.
- Identify any relationships between questions from player responses.

9.1.2 Questions

With a suitable physical testing methodology developed, question phrasing, ball samples, and player selection were finalised. Both feel and performance perceptions were important when considering comparisons asked of players. Instead of isolating a few areas with questions of limited breadth, a series of questions was developed to incorporate a range of properties a player assesses during play. They were developed from interviews with elite players and implied properties elicited from the aesthetic investigation detailed in Chapter 8. From this range of questions, areas players can identify during testing can be noted for future investigations. Question phrasing and suitability were investigated during pilot testing to ensure player comprehension and relevance. These questions can be grouped into three categories:

**Performance - Flight**

Compared to the first ball,

- the flight of the second ball was: more controllable, less controllable, no noticeable difference?
- the spin on the second ball was: more controllable, less controllable, no noticeable difference?
- the second ball travelled: faster, slower, no noticeable difference?

**Performance - Bounce**

Compared to the first ball,

- the second ball bounced: higher, lower, no noticeable difference?

| Table 9.1: Balanced Latin Square for player perception testing. |
|-----------------|-----|-----|-----|-----|-----|-----|
|                 | 1   | 2   | 3   | 4   | 5   | 6   |
| **Comparison**  |     |     |     |     |     |     |
| BC              | AB  | BD  | AC  | CD  | AD  |     |
| AB              | AC  | AD  | BC  | BD  | CD  |     |
| AC              | BC  | CD  | AB  | AD  | BD  |     |
| AD              | CD  | AC  | BD  | AB  | BC  |     |
| BD              | AD  | AB  | CD  | BC  | AC  |     |
| CD              | BD  | BC  | AD  | AC  | AB  |     |

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the second ball bounced: faster, slower, no noticeable difference?

**Feel**

Compared to the first ball,

- the second ball felt: more pleasant, less pleasant, no noticeable difference?
- the second ball felt: softer, harder, no noticeable difference?
- the second ball felt: lighter, heavier, no noticeable difference?
- the second ball was: livelier, deader, no noticeable difference?

Players were allowed to warm up with practice shots and familiarise themselves with the questions during testing, were allowed to answer the questions in any order. A question involving how much spin could be applied to the ball was eliminated as a result of pilot testing as players deemed it too similar to spin controllability. Though nine questions may seem to present a player with much to consider during a comparison, pilot testing indicated players were adequately able to consider all questions and that they reflected relevant areas of feel and performance. The range of questions was also designed to help determine which areas of feel and performance are most significant to players.

Questions involving preference for play were not asked as it was felt these would distract players from perceptible differences in balls. Additionally limitations with only two shots types and relatively static testing were not felt to provide an appropriate preference evaluation. These testing limitations will be discussed further in Chapter 11. In addition to verbal questioning, players were also presented with a written list of questions before and during testing.

### 9.1.3 Ball Characteristics and Preparation

Interviews and aesthetic testing performed in Chapter 8 indicated that ball attributes are often associated together through past experience (e.g. a bald ball is also often flat, or perceived to be so). The two studies looked to isolate conditions such as pressure loss and appearance from each other to independently determine the importance and perception of each.

Differences in ball fuzziness have been shown to affect ball aerodynamics and are a key attribute used by players in ball differentiation as shown in the aesthetic investigation. Pressurised balls are used in all of the Grand Slam Tournaments and were shown by Davies (2005) to have preferred sound and feel properties as compared to pressureless balls. The natural pressure loss that occurs due to the pressure gradient between the core and atmosphere causes this increased internal pressure to diminish over time. Because pressurised balls rely on this air as a form of energy storage, ball properties are subsequently affected.

Characteristics of the balls used in the investigations are shown in Tables 9.2 and 9.3, with letters randomly assigned to each ball condition. The balls used in the age study were standard Slazenger Wimbledon balls opened in advance of testing and stored in controlled conditions until the test date. All balls were pre-compressed according to ITF specifications to eliminate any rubber stiffness resulting from extended storage.

Balls used in the fuzziness study were unmarked Slazenger Wimbledon balls that were manually altered during the 24 hours before testing. Manual alterations were performed to control the surface conditions and minimise any other affects to the ball, such as core stiffness or colour change, occurring with impacts. Bald balls were created by manually removing fuzz with an electric razor. The fuzzy samples were rubbed in a repeated pattern against a racket stringbed to lift fuzz from the cloth covering. The very fuzzy sample was distinguished from the fuzzy sample through its tufted, entangled surface. The fuzzy ball simply had additional long, stringy fibres protruding from the ball’s surface as shown in Figure 9.3. These balls were unmarked as the surface processing would have affected the condition of the ball logo and potentially affected player perceptions as indicated in Chapter 8.
Table 9.2 shows changes to ball mass and fuzziness during testing. Balls B, C, and D showed similar signs of mass loss, indicating that the ball machine and player impacts caused minimal, but similar amounts of wear on the samples (the bald ball showed smaller changes due to the cloth already removed from its surface). The bald balls showed slight increases in fuzziness from play, as fibres were lifted from the ball surface. The new and very fuzzy samples showed similar decreases in fuzziness, though the fuzzy sample showed much higher losses - likely due to the loose fibres easily pulled from the ball’s surface during testing. As the post-test fuzziness values are still similar in order and magnitude between the samples, and the order of the balls used (and worn) during testing was randomised, ball wear during testing can be concluded to be minimal and not an effect in player responses.

![Balls A, B, C, D](image)

**Figure 9.3:** Balls used in fuzz study.

**Table 9.2:** Characteristics of balls used in the fuzz study.

<table>
<thead>
<tr>
<th>Ball</th>
<th>Description</th>
<th>Mass Loss (g)</th>
<th>Fuzziness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Processing</td>
<td>Testing</td>
</tr>
<tr>
<td>A</td>
<td>Bald</td>
<td>0.487 (0.021)</td>
<td>0.040 (0.010)</td>
</tr>
<tr>
<td>B</td>
<td>New</td>
<td>0.110 (0.036)</td>
<td>0.103 (0.031)</td>
</tr>
<tr>
<td>C</td>
<td>Very Fuzzy</td>
<td>0.157 (0.038)</td>
<td>0.103 (0.031)</td>
</tr>
<tr>
<td>D</td>
<td>Fuzzy</td>
<td>0.107 (0.045)</td>
<td>0.090 (0.017)</td>
</tr>
</tbody>
</table>

*Note: standard deviations given in parentheses.*

**Table 9.3:** Characteristics of balls used in the natural ageing study.

<table>
<thead>
<tr>
<th>Ball</th>
<th>Description</th>
<th>Bounce (cm)</th>
<th>Fwd Cmp (mm)</th>
<th>Ret Cmp (mm)</th>
<th>Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>One Month</td>
<td>133.27 (1.02)</td>
<td>0.253 (0.007)</td>
<td>0.345 (0.008)</td>
<td>122.25 (5.10)</td>
</tr>
<tr>
<td>B</td>
<td>One Week</td>
<td>135.93 (0.67)</td>
<td>0.237 (0.005)</td>
<td>0.322 (0.006)</td>
<td>136.56 (5.73)</td>
</tr>
<tr>
<td>C</td>
<td>New</td>
<td>138.54 (1.03)</td>
<td>0.240 (0.010)</td>
<td>0.323 (0.009)</td>
<td>137.10 (5.45)</td>
</tr>
<tr>
<td>D</td>
<td>Three Months</td>
<td>132.61 (0.86)</td>
<td>0.254 (0.006)</td>
<td>0.360 (0.008)</td>
<td>118.34 (4.20)</td>
</tr>
</tbody>
</table>

*Note: standard deviations given in parentheses.*

### 9.1.4 Player Selection

Fifteen experienced male and female tennis players were used from the Loughborough University Tennis first and second teams. Subjects had an average age of 19.60 (σ = 1.68) with 12 years of playing experience (σ = 2.9) and LTA ratings between 2.2 and 5.1. These rankings are based on recent tournaments and the lower rankings for some players is due to their focus on the University season and lack of recent tournament play. All players were of at least county standard, with most possessing regional and national experience.

Players were allowed to use their own rackets during testing so they would be familiar with racket characteristics during play. All players used a tension between 25-27.3kg (55-60lbs) with most using either polyester or synthetic gut string.
9.2 Shot Performance

The scoring method was used to evaluate differences in shot outcome and assess if poor shot scores influenced any player evaluations. Two methods of analysis were used with the shot scores. Initial analysis looked to determine if a certain ball was rated differently because players struggled with shot placement. Table 9.4 indicates that for each of the shot types and studies, none of the ball types were hit significantly differently than the others. Differences were calculated using Friedman's test, a non-parametric alternative to an ANOVA analysis allowing for repeated measures. This is further discussed in Appendix C.

Table 9.4: Friedman analysis (p-values) on ball shot scores.

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Fuzz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehand</td>
<td>0.545</td>
<td>0.890</td>
</tr>
<tr>
<td>Serve</td>
<td>0.488</td>
<td>0.348</td>
</tr>
</tbody>
</table>

A second concern was that players may have struggled to adapt to certain balls based on the comparison they were making (e.g. A bald ball could travel very quickly for the first three shots and a very fuzzy ball could then travel very slowly for the second three shots. The player may then struggle to adjust and thus play the ball poorly). To analyse these differences, the difference in average shot score for the three shots was calculated for each comparison. Friedman's test was used to examine any differences in the ball comparisons and players involved in the studies, with results shown in Table 9.5. No significant differences were found between the comparisons, indicating the players did not struggle to adjust to ball comparisons during testing. Main effects were found between individual players for the forehand during the age study, suggesting some players were affected by scoring differences during this portion of testing. Further post-hoc analysis, however, indicated no significant differences at $p < 0.05$. As there were no significant differences in shot outcome for the studies and shots performed player perceptions were deemed not to have been affected by shot performance.

Table 9.5: Friedman analysis (p-values) on ball comparisons.

<table>
<thead>
<tr>
<th>Players</th>
<th>Comparison</th>
<th>Age</th>
<th>Fuzz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehand</td>
<td></td>
<td>0.013</td>
<td>0.137</td>
</tr>
<tr>
<td>Serve</td>
<td></td>
<td>0.424</td>
<td>0.082</td>
</tr>
</tbody>
</table>

9.3 Player Consistency

Subject consistency can be evaluated through triads, or the choices made between three objects in given study. A 'preference graph', developed by Kendall & Babington Smith (1940), allows the choices from a subject's preference matrix, shown in Table 9.6, to be mapped onto a visual diagram.

Inconsistencies occur when a subject identifies preferences that form a circular triad, as in Table 9.6 between balls A, B, and D. This triad is the equivalent of a subject stating: A is preferred to B, B is

Table 9.6: Preference matrix and visual diagram for flight speed responses.

<table>
<thead>
<tr>
<th>Faster</th>
<th>Ball</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
preferred to D, and D is preferred to A, inducing false logic. Kendall & Babington Smith (1940) define the coefficient of consistence for a given subject in Equation 9.1 for \( t \) objects and \( c_t \) circular triads.

\[
\zeta = 1 - \frac{24c_t}{t(t^2 - 1)} \quad \text{for } t \text{ odd and } \zeta = 1 - \frac{24c_t}{t(t^2 - 4)} \quad \text{for } t \text{ even} \tag{9.1}
\]

The no difference option given to participants complicated the analysis of inconsistent responses and made the Kendall coefficient of consistency, used with binary data, inappropriate. Previous work has randomly assigned ‘no difference’ responses to the two choices, but this random element does not help eliminate inconsistent subjects from data analysis (David, 1988).

Davies (2005) develops a scoring system to assess triads incorporating the ‘no difference’ response. For three objects, there are 27 distinct triads that can be formed, but these can be grouped into corresponding triad groups with associated scores as shown in Table 9.7. These scores are based on the probability a circular triad would be formed if a subject was forced to choose between the options. For four objects, the maximum number of circular triads that can be formed is two. The scores from the four triads in each preference diagram are summed to form a score ranging from 0 to 2, which can then be used in Equation 9.1 for \( t = 4 \).

### 9.3.1 Removal of Inconsistent Players

When considering all 36 triads encompassing both studies and both shot types, there was only one player who was completely consistent. These inconsistencies can be attributed to differing abilities to determine

<table>
<thead>
<tr>
<th>Type</th>
<th>Example</th>
<th>Score</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>True consistent</td>
<td>C preferred to A</td>
<td>0</td>
<td>6/27</td>
</tr>
<tr>
<td></td>
<td>C preferred to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One clear winner</td>
<td>C preferred to A</td>
<td>0</td>
<td>3/27</td>
</tr>
<tr>
<td></td>
<td>C preferred to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No difference A &amp; B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One clear loser</td>
<td>C preferred to A</td>
<td>0</td>
<td>3/27</td>
</tr>
<tr>
<td></td>
<td>B preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No difference B &amp; C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equality</td>
<td>No difference A &amp; B</td>
<td>0.25</td>
<td>1/27</td>
</tr>
<tr>
<td></td>
<td>No difference A &amp; C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>No difference B &amp; C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two ties</td>
<td>No difference A &amp; B</td>
<td>0.25</td>
<td>6/27</td>
</tr>
<tr>
<td></td>
<td>No difference A &amp; C</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C preferred to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconsistency with</td>
<td>A preferred to B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>one tie</td>
<td>C preferred to A</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>No difference B &amp; C</td>
<td></td>
<td>6/27</td>
</tr>
<tr>
<td>Circular triad</td>
<td>A preferred to B</td>
<td>1</td>
<td>2/27</td>
</tr>
<tr>
<td></td>
<td>C preferred to A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B preferred to C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
flight, bounce, and feel properties, as well as differences in the ball characteristic under investigation.

To determine the suitability of each subject’s responses for future data analysis, a singular triad was identified from each study to determine if a subject was adequate in assessing ball differences. This triad included the new ball from each study, as well as two other samples that were seen to be the ‘most’ different from the new ball. If a subject could consistently answer 14 of 18, questions in a given study for this triad, they were deemed suitable participants. This produced minimum coefficient of consistency of \( \zeta = 0.78 \) for each of the subjects included in future analysis. This is above the average consistency of \( \zeta = 0.75 \) recommended by Otto et al. (2001). The age study used the new ball, the one month ball, and the the three month ball, while the fuzz study used the new ball, the bald ball, and the very fuzzy ball. The number of circular triads for each player in the studies is shown in Table 9.8. Subject 12 was removed from the age study and subjects 7 and 13 were removed from the fuzz study due to high inconsistency scores.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Natural Ageing</th>
<th>Fuzz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Serve</td>
<td>Forehand</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 9.3.2 Differences in Consistency

Friedman’s test was used as a non-parametric alternative to a two-way ANOVA to determine significant differences in player consistency. Differences in columns are examined, while accounting for row effects and repeated measures. To test for row effects, the transpose of the data matrix can be examined.

#### Shot Differences

Subjects were significantly more consistent with the serve as compared to the forehand \( (p=0.004) \) as players were allowed to touch, squeeze, and bounce the balls before playing with them. These capabilities potentially aided players in their ability to differentiate between balls, making them more consistent.

It is interesting that the three inconsistent players were all more inconsistent on the serve than the forehand, opposing the trend exhibited by other players. It could be that instead of reinforcing perceptions noted during the forehand shot, the presence or absence of aesthetic differences in the balls confused some of the subjects and created more inconsistencies.

#### Study Differences

Subjects were significantly more consistent throughout the questions and shots in the fuzz study than the age study \( (p < 0.001) \). This could be due to the aesthetic differences in the balls that make differences
in ball performance and feel more apparent to players. Ball age could also be less perceptible to players, therefore contributing to increased inconsistencies.

**Question Differences**

Significant differences exist between questions ($p = 0.001$), suggesting that some areas of feel and performance were more noticeable during testing. Further post-hoc analysis indicated that ball flight speed produced significantly more consistent responses than flight and spin control, bounce height, pleasantness, and ball weight.

### 9.4 Agreement within Questions

Agreement between subject responses can be calculated using the scores from the preference matrix, shown in Table 9.9, and Kendall’s coefficient of agreement (Kendall & Babington Smith, 1940). The range of this coefficient, for four balls, is -0.5 to 1.0. Rankings with significance are determined with the Friedman statistic according to the $\chi^2$ distribution. Further details are located in Appendix C. Table 9.10 shows the agreement between subjects during testing, with significant results highlighted.

Table 9.10 indicates that the fuzz study produced more significant observations and generally had higher coefficient of agreement values. These values suggest players were better at identifying differences in fuzzy ball samples and had better agreement on how they differed. This is likely because of the visible differences present in the fuzz samples, not present in the aged balls, allowing players to either infer or detect differences more readily.

Friedman’s test, used instead of an ANOVA test which relies on a normal distribution, indicated a significant effect due to questions ($p = 0.025$), though further post-hoc analysis indicated no significant differences ($p < 0.05$).

#### Table 9.9: Example preference matrix and corresponding rank sums for travel speed.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.5</td>
<td>1</td>
<td>1</td>
<td></td>
<td>6.5</td>
</tr>
<tr>
<td>B</td>
<td>8.5</td>
<td>1</td>
<td>3</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>12</td>
<td>10</td>
<td>3</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>32.5</td>
<td>26.5</td>
<td>5</td>
<td>14</td>
<td>51</td>
</tr>
<tr>
<td>Rank Sum</td>
<td>71.5</td>
<td>65.5</td>
<td>44</td>
<td>53</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 9.10: Kendall’s coefficient of agreement for player responses.

<table>
<thead>
<tr>
<th></th>
<th>Natural Ageing</th>
<th>Fuzz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forehand</td>
<td>Serve</td>
</tr>
<tr>
<td>Flight Control</td>
<td>-0.001</td>
<td>-0.004</td>
</tr>
<tr>
<td>Spin Control</td>
<td>-0.061</td>
<td>0.054</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>0.080</td>
<td>0.039</td>
</tr>
<tr>
<td>Bounce Height</td>
<td>0.039</td>
<td>-0.038</td>
</tr>
<tr>
<td>Bounce Speed</td>
<td>0.005</td>
<td>-0.038</td>
</tr>
<tr>
<td>Pleasantness</td>
<td>-0.027</td>
<td>-0.023</td>
</tr>
<tr>
<td>Hardness</td>
<td>0.051</td>
<td>0.090</td>
</tr>
<tr>
<td>Weight</td>
<td>0.019</td>
<td>-0.005</td>
</tr>
<tr>
<td>Liveliness</td>
<td>-0.012</td>
<td>0.010</td>
</tr>
</tbody>
</table>
9.5 Determination of Merit Values

While scores for each of the balls can be obtained directly from the preference matrices, these scores do not provide information on how one ball was judged against another and cannot be directly compared with objective data (Otto et al., 2001). Probabilistic choice models derive ratio scale measures of objects involved in a paired comparison study from the binary comparison judgements resulting from the comparisons. These ratio scale measures can be seen as merit values for the relative worth of each ball on a linear scale and indicate significant differences between balls. While there are several popular models used with paired comparison data, the two most popular are the Bradley-Terry model, developed by Bradley & Terry (1952) with contributions from Luce (1959), and the Thurstone-Mosteller model (Mosteller, 1951; Thurstone, 1927). Both models are examples of generalised linear models, though the Thurstone-Mosteller model assumes a normal distribution and the Bradley-Terry a logistic one.

Stern (1992) indicates that the distribution used to fit the linear model is not as important as the appropriateness of a linear model to model the data. This can be evaluated using Pearson's correlation coefficient to compare merit values with the raw data. The Bradley-Terry model is seen as an appropriate model if it can be assumed that all the objects under investigation are judged according to the same criteria and the importance of these criteria remain constant throughout the comparisons made. This context independence can be assumed to fit the studies as the ball samples are largely heterogenous and vary only by one attribute. Merit values in the Bradley-Terry model are produced through preference probabilities determined through scale values, as shown in Equation 9.2.

\[
\begin{align*}
    p_{ab} &= \frac{\nu(a)}{\nu(a) + \nu(b)}
\end{align*}
\] (9.2)

The Bradley-Terry model was applied to each of the score matrices using an algorithm developed for MATLAB by Wickelmaier & Schmid (2004). Scores of 'no difference' were evenly distributed during the fitting process as the algorithm, and other available computer scripts, require binary data.

Figures 9.4 through 9.12 show these merit values plotted on a linear scale with the standard error associated with each value. Values separated by more than two standard errors can be considered significantly different. The fit of the model may be analysed by examining the Pearson correlation coefficient of the model against the raw data, shown in Table 9.11. Otto et al. (2001) recommend a fit of \( r = 0.9 \) for most computer fit models, though also add that no linear model will do well where a number of inconsistencies are found. While the majority of the fits in Table 9.11 are above this threshold, those below this are related to questions indicating inconsistent responses in Section 9.3.2 (natural ageing study, ball weight, bounce height, pleasantness, flight control). Zimmer et al. (2004) detail the use of the \( \chi^2 \) statistic as a measure of data departures from the model, with an upper probability of \( p = 0.10 \) indicating poor fit (Wickelmaier & Schmid, 2004). All but two of the \( \chi^2 \) values in Table 9.11 are above this level. The poor fits are attributed to an inconsistently assessed ball property, pleasantness, and the poor sample differentiation noted with the naturally aged balls during the forehand. The results, however, indicate that the Bradley-Terry model generally shows good fit with much of the experimental data. It should be noted that in the following discussion, 'in order of fuzziness' considers the tufted fuzz ball (very fuzzy) ball as the fuzziest ball sample.

Flight Control

No significant differences were found between any of the balls. In both studies, the serve produced a different ordering of balls as compared to the forehand - suggesting aesthetic and tactile attributes affect player perceptions. The lack of consistent ball ordering for both studies could also suggest varied perceptions of control between players for different shots.
Figure 9.4: How controllable was the flight of the ball?

Figure 9.5: How controllable was the spin of the ball?

Figure 9.6: How fast did the ball travel?
Figure 9.7: How high was the bounce of the ball?

Figure 9.8: How fast was the bounce of the ball?

Figure 9.9: How pleasant did the ball feel?
Figure 9.10: How hard was the ball?

(a) Fuzz.

(b) Natural Ageing.

Figure 9.11: How heavy was the ball?

(a) Fuzz.

(b) Natural Ageing.

Figure 9.12: How lively was the ball off the racket face?
### Table 9.11: Pearson correlation and $\chi^2$ values for Bradley-Terry model fit.

<table>
<thead>
<tr>
<th></th>
<th>Pearson correlations</th>
<th></th>
<th>$\chi^2$ probabilities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Age</td>
<td>Fuzz</td>
<td>Age</td>
<td>Fuzz</td>
</tr>
<tr>
<td></td>
<td>Serve</td>
<td>Forehand</td>
<td>Serve</td>
<td>Forehand</td>
</tr>
<tr>
<td>Control</td>
<td>0.961</td>
<td>0.917</td>
<td>0.885</td>
<td>0.961</td>
</tr>
<tr>
<td>Spin</td>
<td>0.961</td>
<td>0.986</td>
<td>0.999</td>
<td>0.983</td>
</tr>
<tr>
<td>Speed</td>
<td>0.939</td>
<td>0.954</td>
<td>0.996</td>
<td>0.998</td>
</tr>
<tr>
<td>Bounce Height</td>
<td>0.897</td>
<td>0.882</td>
<td>0.996</td>
<td>0.962</td>
</tr>
<tr>
<td>Bounce Speed</td>
<td>0.996</td>
<td>0.924</td>
<td>0.979</td>
<td>0.994</td>
</tr>
<tr>
<td>Pleasantness</td>
<td>0.973</td>
<td>0.890</td>
<td>0.852</td>
<td>0.949</td>
</tr>
<tr>
<td>Hardness</td>
<td>0.916</td>
<td>0.853</td>
<td>0.984</td>
<td>0.973</td>
</tr>
<tr>
<td>Weight</td>
<td>0.911</td>
<td>0.892</td>
<td>0.980</td>
<td>0.987</td>
</tr>
<tr>
<td>Liveliness</td>
<td>0.908</td>
<td>0.903</td>
<td>0.987</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.606</td>
<td>0.377</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.728</td>
<td>0.416</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.423</td>
<td>0.895</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.558</td>
<td>0.167</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.994</td>
<td>0.230</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.768</td>
<td>0.276</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.285</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.283</td>
<td>0.293</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.294</td>
<td>0.360</td>
</tr>
</tbody>
</table>

### Spin Control

The spin on the very fuzzy sample was significantly less controllable than the new and bald ball during a forehand. During the serve, however, merit values were in order of ball fuzziness with the very fuzzy ball deemed to have the most controllable spin. Differences could be due to differing abilities to apply spin to a moving and stationary ball. Both studies show improved spacing of merit values for the serve, again indicating that perhaps handling the balls allowed players to better differentiate between balls. The age study did not have any significant differences or consistent ball ordering between shots.

### Travel Speed

In both studies, the serve showed better differentiation in merit values. The two fuzzy samples travelled significantly slower than the new and bald balls on the forehand, and than the bald ball on the serve. Ball ordering is from fuzziest to baldest for both shots. Ball ordering in the age study did not agree with the age of the balls as the three month ball was rated the slowest and the one month ball the fastest.

### Bounce Height

The ordering of the balls indicates players perceive fuzzier and older tennis balls to bounce lower. The very fuzzy ball bounced significantly lower than the new and bald samples, though there were no significant differences in the aged samples. The fuzz study showed better ball differentiation for both shots.

### Bounce Speed

The very fuzzy ball showed a significantly slower bounce than the new and bald samples, with ordering related to ball fuzziness in both shots. The age samples showed no significant differences between balls and the new ball was rated noticeably faster on the serve than with the forehand. Again, this is attributed to player ability to handle the balls.

### Pleasantness

The very fuzzy ball was significantly less pleasant than the new ball for both shots. Ball ordering in the fuzz study went from very fuzzy, fuzzy, bald, to new. It is possible that the visual recognition of the new ball caused players to rate it more favourably, as the age study showed no significant differences and no consistent ball order. It is hypothesised that aesthetic differences influenced player perceptions of ‘pleasantness’ and the similar appearance of aged balls prevented players from making consistent decisions.
Hardness

Both fuzzy balls were significantly softer than the new and bald balls (both shots), though only on the serve was the three month ball softer than the new ball. The three month ball was the only ball with an unchanging position during the age study. It is possible the other balls were more difficult to differentiate and handling allowed players to make more consistent decisions.

Weight

Ball ordering for the fuzzy samples was in order of fuzziness, with fuzzy samples perceived to be heavier. The bald ball was significantly lighter than the very fuzzy sample. The aged samples did not show consistent ordering between shots and there were no significant differences present. Similar to other areas of feel and performance, it is believed aesthetic differences improved player ability to differentiate samples

Liveliness

The fuzz study indicated both fuzzy balls were significantly deader than the new and bald balls in the forehand. A noticeable change occurred with the serve as the bald ball was significantly livelier than all other samples and the new ball perceived to be deader. No significant differences were present in the age study and ball ordering varied greatly between the shots.

9.6 Player Reliability

Similar ball evaluations in both shots can be seen as a measure of player ability to perceive and identify ball properties. This capability may differ depending on the property under investigation, but could be used as a method to determine subject suitability for future studies in their potential to identify ball differences. There is no current method to determine the suitability of test subjects for perception testing in tennis, except for their standard of play, which was used in this study.

Based on the evaluations for the six ball pairs, rank values for each of the samples can be identified for each player based on how often a ball is ‘preferred’ over another. A ball’s score was given a +1 each time it was preferred over another and a +0.5 each time a no difference was indicated, as shown in Figure 9.13. These scores were ranked from 1 to 4 for both the forehand and serve. Spearman’s rank-order correlation, a non-parametric association between two values, was used to determine associations between the shots. The correlation can range from +1 to -1, indicating strong positive or negative agreement between the shots. Further details are given in Appendix C.

The fuzz study showed significantly (p = 0.001) higher consistency between the two shots than the age study, indicating aesthetic differences improved player reliability. There were no significant differences in the age study for either questions (p = 0.727) or players (p = 0.156). The fuzz study, however, indicated differences in player reliability (p < 0.001) and questions (p < 0.001). Player 15 was significantly more reliable than players 1 and 2, and player 9 was more reliable than player 2. Both travel speed and bounce
speed produced more reliable responses than flight and spin control, making these areas useful in the future design of player studies.

9.7 Relationships between Questions

To determine associations between questions, individual player responses were analysed. The scoring system developed in the previous section was used for each shot in each study to create sixteen paired ranks for comparison. Spearman's rank order correlation coefficient was calculated for the thirty-six possible relationships between questions for each player. Table 9.12 shows the average correlation magnitudes for all players, with significant values highlighted in red. Significance was determined according to Spearman's critical value \( r_p = 0.497 \) at \( \alpha = 0.05 \) for 16 comparisons. As Spearman's correlation coefficient can range from -1 to +1, absolute values were used in determining relationship averages to prevent strong negative and strong positive correlations from offsetting each other. Significant relationships are discussed below and apply to all significant responses received. Where a percentage is given, players indicating significant correlations between questions did not agree on the direction of the relationship.

Table 9.12: Average Spearman correlation coefficients for all players. Significant values given in red.

<table>
<thead>
<tr>
<th>Flight control</th>
<th>Spin control</th>
<th>Flight speed</th>
<th>Bounce height</th>
<th>Bounce speed</th>
<th>Pleasantness</th>
<th>Hardness</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin control</td>
<td>0.691</td>
<td>0.394</td>
<td>0.420</td>
<td>0.374</td>
<td>0.638</td>
<td>0.416</td>
<td>0.470</td>
</tr>
<tr>
<td>Flight speed</td>
<td>0.464</td>
<td>0.455</td>
<td>0.435</td>
<td>0.670</td>
<td>0.476</td>
<td>0.490</td>
<td>0.444</td>
</tr>
<tr>
<td>Bounce height</td>
<td>0.701</td>
<td>0.840</td>
<td>0.594</td>
<td>0.777</td>
<td>0.584</td>
<td>0.823</td>
<td></td>
</tr>
<tr>
<td>Bounce speed</td>
<td>0.749</td>
<td>0.590</td>
<td>0.666</td>
<td>0.541</td>
<td>0.687</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pleasantness</td>
<td>0.582</td>
<td></td>
<td>0.729</td>
<td>0.594</td>
<td>0.809</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td></td>
<td>0.535</td>
<td>0.549</td>
<td>0.618</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td></td>
<td>0.553</td>
<td>0.755</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liveliness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.581</td>
<td></td>
</tr>
</tbody>
</table>

Players strongly associated more controllable flight with more controllable spin, with increased control in each of these areas linked to a more pleasant feel. Responses indicating more controllable spin were, however, equally divided between lighter and heavier balls. Faster flight speed was strongly associated with a higher, faster bounce, a harder ball, and increased pleasantness and liveliness. Seventy-five percent of significant responses related a slower travel speed to a heavier ball. A high ball bounce was strongly associated with a faster one. A higher, faster ball bounce was correlated with a harder, livelier, more pleasant ball. A heavier ball was linked by many participants to a lower (70% of responses), slower (73% of responses) bounce. More pleasant impacts were linked to a harder, livelier ball, with 78% of responses indicating a heavier ball. Players were equally divided between associating a softer ball with a dead or lively one. All responses indicated a harder ball was also a livelier one. Eighty percent of significant responses also indicated a lighter ball to be more lively.

9.8 Concluding Comments

Research performed in this chapter provides information on player perception abilities concerning two areas of ball degradation and for two shots. An assessment of player consistency, reliability, and agreement in responses provides information regarding both important areas of player perception, as well as indistinguishable ones. A summary of important conclusions is discussed below.

- Players indicated more consistent responses with the service shot and fuzzy tennis balls. This suggests that handling balls, as well as higher impact speeds, play an important role in player perception. The increased agreement in evaluations in the fuzzy study also indicates that aesthetic differences in balls allow players to remain more consistent in their responses.
• Questions showing good agreement between players, good consistency, and good differentiation in merit values included ball travel speed and hardness. Bounce height and bounce speed showed improved differentiation with aesthetic differences in balls. With regards to feel, ball liveliness showed improved differentiation as opposed to ball pleasantness. Flight and spin control produced unreliable and inconsistent responses.
• The strong relationships between many of the perceived feel and performance questions indicates players make strong associations between a variety of ball properties.

The following chapter compares results determined from perception testing in this chapter with measures of ball performance and ball degradation. Results of these comparisons will help determine areas of player perception most suited to producing good responses from players and measurable differences between balls.
Chapter 10

Evaluation of Perception and Performance Data

This chapter presents an evaluation of player perception and ball performance data to determine relationships between objective ball measures and subjective assessments by players. Several objective measures of ball degradation are used to form these relationships: impact properties, aerodynamic data, and direct measures of ball degradation such as surface roughness and age. Along with comparisons to player perception data, performance data is related to ball degradation characteristics and examined with respect to ball feel. The chapter concludes with a discussion of the most important characteristics in player perception of ball degradation identified as a result of these evaluations.

10.1 Evaluation Method

Three different comparisons are made in this chapter during the evaluations of player perception, ball performance data, and direct measures of ball degradation. Significant differences in the dependent variable listed in Table 10.1 are used to determine values of ball degradation measures and performance data needed to create this differentiation. Although some relationships are known to be non-linear (such as between aerodynamic data and the digital fuzziness metric and between natural pressure loss and time), the limited number of samples available for examination restricts the analysis to linear assumptions. Pearson's correlation coefficient, detailed in Appendix C, was used to evaluate these linear relationships.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>Evaluation hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance data</td>
<td>Degradation measures</td>
<td>Ball roughness and age correspond to significant differences in measured performance data. Significant relationships will suggest that differences in performance are created by measured differences in ball fuzziness and age.</td>
</tr>
<tr>
<td>Perception merit values</td>
<td>Performance data</td>
<td>Significant differences in perceived ball properties relate to differences in ball performance properties. Strong relationships will suggest that player perception can be indicated from measured performance data.</td>
</tr>
<tr>
<td>Perception merit values</td>
<td>Degradation measures</td>
<td>Differences in perceived ball properties correlate with ball with direct measures of ball degradation. Strong associations will suggest player perception can be determined from measured values of ball roughness and age.</td>
</tr>
</tbody>
</table>

Two levels of significance are discussed for these comparisons. As there were only four sets of points used in comparisons, a value of $r = 0.90$ was required for significance above the $\alpha = 0.10$ level and a value of $r = 0.80$ required for significance above $\alpha = 0.20$. Significant areas determined from existing data includes correlations with $r \geq 0.90$. Promising areas with $r \geq 0.80$ are also discussed as they indicate regions
Figure 10.1: Examples of determining thresholds creating significant differences in objective and perceptive evaluations.

where further work with increased numbers of samples may solidify relationships. Significant correlations ($r \geq 0.90$) were fit with a best fit line and significant differences on the $x$-axis used to determine differences in values along the $y$-axis. The minimum significant differences for each dependent variable were used to determine thresholds in the independent variable. Figure 10.1 shows examples of this analysis for objective and perception data for fuzzy ball samples during a service. It should be noted that perceptible thresholds could be below these levels, but comparisons were limited to the balls and shots used in perception testing. These differences, however, still provide useful information on levels of degradation and differences in performance properties.

### 10.2 Evaluation of Objective Data

This section examines any relationships between experimental data and direct measures of ball degradation. Impact data is directly correlated with degradation measures, such as ball fuzziness and age, to determine if a direct linear relationship exists. Experimental data has been correlated with ball roughness (mm) and age (days). Significant areas are indicated in blue, and promising areas indicated in red in Table 10.2. Results suggest that very few of the measured ball characteristics linearly correlate with ball fuzziness and age. Promising areas include peak force for fuzzy balls and stiffness for aged balls. Peak force results for the aged balls also indicate a potential relationship that could be solidified with future testing.

<table>
<thead>
<tr>
<th>Table 10.2: Relationship of experimental data with ball fuzziness (mm) and age (days).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Racket COR</td>
</tr>
<tr>
<td>COR</td>
</tr>
<tr>
<td>Spin</td>
</tr>
<tr>
<td>Stiffness</td>
</tr>
<tr>
<td>Damping</td>
</tr>
<tr>
<td>Peak force</td>
</tr>
<tr>
<td>Contact time</td>
</tr>
</tbody>
</table>

Significant correlations were considered for their relationship with measurable differences in ball fuzziness and age. Measurable differences in racket COR and ball damping occur with differences in ball fuzziness of 2.30mm and 3.23mm, respectively, for the serve. Differences in peak impact force for both the forehand
and service shots occur with a roughness difference of 1.87mm. Ball stiffness and peak force indicate measurable differences due to natural ageing after 63 and 33 days, respectively. It should be noted that natural ageing assumes a linear relationship with regards to pressure loss and experimental data, despite the non-linear trends observed in Section 5.3.3. Further work is required to either affirm the linear relationship or develop a non-linear one.

10.2.1 Dynamic Properties and Ball Feel

Haake & Goodwill (2002) propose that improved ball feel is related to increased ball stiffness and COR. This relationship is examined with impact data for each of the balls used in player testing. Figure 10.2 shows that the balls used in testing do not show the same range of stiffness and COR previously documented, though they are consistent with the general linear trend of the data.

Perception data gathered in Chapter 9 for ball 'pleasantness' indicated inconsistent responses, poor player agreement, and no significant differences between balls. While a broader range of ball samples may have produced more successful responses - the influence of impact sound and vibration documented by Davies (2005) and the importance of ball aesthetic attributes noted in Chapter 8 make it unlikely that this relationship will ever reflect general player agreement on 'better feel'. This is supported by the inconsistent responses noted in Chapter 9 for 'more pleasant' impacts.

![Figure 10.2: Relationship of experimental data with Haake's (2002) hypothesis on ball feel.](image)

10.3 Evaluation of Perception Results

This section uses Pearson's correlation coefficient to compare merit values determined from player testing performed in Chapter 9 with objective ball data. Relationships with ball performance data and direct measures of ball condition are discussed in the following sections.

10.3.1 Correlation with Dynamic Ball Properties

Ball 'feel' areas, including liveliness, hardness, weight, and pleasantness, were related to impact properties determined from the acceleration plate. Perceived performance areas, including ball bounce and flight, were correlated with rebound properties (COR and spin) and aerodynamic data.
Table 10.3: Pearson values for experimental and perception data.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Perception</th>
<th>Fuzz</th>
<th>Natural Ageing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Forehand</td>
<td>Serve</td>
</tr>
<tr>
<td>Flight speed</td>
<td>$C_D$</td>
<td>-0.881</td>
<td>-0.964</td>
</tr>
<tr>
<td>Flight control</td>
<td>$C_D$</td>
<td>-0.553</td>
<td>0.574</td>
</tr>
<tr>
<td></td>
<td>Racket COR</td>
<td>0.332</td>
<td>-0.954</td>
</tr>
<tr>
<td></td>
<td>COR</td>
<td>-0.410</td>
<td>-0.855</td>
</tr>
<tr>
<td>Spin control</td>
<td></td>
<td>0.181</td>
<td>0.289</td>
</tr>
<tr>
<td>Liveliness</td>
<td>Racket COR</td>
<td>0.621</td>
<td>0.863</td>
</tr>
<tr>
<td></td>
<td>COR</td>
<td>-0.090</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>Stiffness</td>
<td>-0.121</td>
<td>-0.767</td>
</tr>
<tr>
<td></td>
<td>Damping</td>
<td>-0.464</td>
<td>-0.981</td>
</tr>
<tr>
<td></td>
<td>Peak force</td>
<td>-0.795</td>
<td>-0.963</td>
</tr>
<tr>
<td></td>
<td>Contact time</td>
<td>-0.603</td>
<td>0.962</td>
</tr>
<tr>
<td>Hardness</td>
<td></td>
<td>0.155</td>
<td>-0.289</td>
</tr>
<tr>
<td></td>
<td>Stiffness</td>
<td>-0.449</td>
<td>-0.990</td>
</tr>
<tr>
<td></td>
<td>Damping</td>
<td>-0.736</td>
<td>-0.973</td>
</tr>
<tr>
<td></td>
<td>Peak force</td>
<td>-0.099</td>
<td>0.271</td>
</tr>
<tr>
<td></td>
<td>Contact time</td>
<td>-0.316</td>
<td>-0.384</td>
</tr>
<tr>
<td>Pleasantness</td>
<td></td>
<td>0.362</td>
<td>0.363</td>
</tr>
<tr>
<td></td>
<td>Stiffness</td>
<td>-0.672</td>
<td>-0.696</td>
</tr>
<tr>
<td></td>
<td>Damping</td>
<td>-0.658</td>
<td>-0.718</td>
</tr>
<tr>
<td></td>
<td>Peak force</td>
<td>-0.316</td>
<td>-0.384</td>
</tr>
<tr>
<td></td>
<td>Contact time</td>
<td>-0.098</td>
<td>0.147</td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td>0.057</td>
<td>0.190</td>
</tr>
<tr>
<td>Bounce speed</td>
<td>COR</td>
<td>0.180</td>
<td>0.418</td>
</tr>
<tr>
<td>Bounce height</td>
<td></td>
<td>0.180</td>
<td>0.418</td>
</tr>
</tbody>
</table>

Table 10.3 presents the correlations of merit values with dynamic ball properties. Significant areas are again indicated in blue, with promising areas highlighted in red. The serve showed stronger agreement with experimental data, especially in the fuzz study. While improved experimental differentiation can be solely attributed to increased ball speed, the addition of a tactile element to the service makes it difficult to determine if players are 'perceiving' differences or if responses are a result of tactile and aesthetic attributes. Stronger relationships with experimental data and perceptions during the fuzz study were likely to be a combination of improved consistency, reliability, and differentiation in player responses. Davies (2005) found that ball stiffness is strongly related to ball control and damping is strongly related to perceived ball weight. Neither stiffness nor damping was related to pleasantness, hardness, or liveliness.

For the fuzziness study, the static drag coefficient indicates significant agreement for the serve and strong agreement for the forehand. Data suggests perceptible differences emerge during the serve for changes in the drag coefficient of 0.08. There were no significant relationships between drag values with perceived flight control. Racket COR showed significant agreement with the serve, though the low value for the forehand suggests this playing property could be more important during the service. The serve also showed some indication of a correlation with rigid plate COR. As there were no significant differences in perceived flight control, no perceptive thresholds could be determined. Spin control was not related to measured spin values at either testing speed. While ball liveliness displayed a weak relationship with racket COR for the serve, the forehand relationship is too low to be considered. Player data did, however, demonstrate strong agreement with ball damping, peak force, and contact time. Thresholds of player perception were calculated to be 1.59Nsm$^{-1}$ and 119N during a serve. Ball hardness exhibited strong correlation with measured ball damping (1.14Nsm$^{-1}$) and peak force (85N), but only for the serve. There was no relationship for any of the impact properties and ball pleasantness. Both damping (2.39Nsm$^{-1}$) and peak force (187N) showed significant agreement with ball weight during the serve, but the additional agreement indicated by peak force during the forehand suggests it may be a more useful relationship.
Neither bounce speed nor bounce height supported a relationship with experimental data. It is suggested that further oblique impact work may provide more relevant data to these properties.

The natural ageing study showed noticeably fewer agreements with experimental data. This lack of agreement is partially attributed to the 'invisible' nature of pressure loss that is not as readily apparent as ball fuzziness. Neither ball flight nor spin control showed any relationship with COR or spin data. Ball liveliness, however, showed a potential relationship with both racket and rigid plate COR for a serve. Hardness also indicated similar agreement for all four impact properties in both shots. As both shots indicate some agreement, it is suggested that this is a promising area for future work. Ball liveliness displayed some correlation with contact time but there was no relationship between ball pleasantness and any of the measured impact properties. Ball weight showed a potential relationship with stiffness and contact time data, the two impact properties for which no significant relationship was found in the fuzz study. Although rigid plate COR demonstrated no relationship for bounce speed in either shot, it did indicate a strong correlation with bounce height for both shots. Unfortunately, players did not indicate perceptible differences in bounce height for either shot.

Several conclusions concerning experimental and perception relationships can be identified from the data in both studies. The fuzz study showed good agreement between flight speed and drag values, though the differences indicated in the natural ageing study cannot be explained in this manner. As the ageing study showed no agreement with racket COR, it can be assumed that tactile information played an important role in perceived control during the service shot of the fuzz study. This is supported by information gathered in Section 8.3 that players considered balder balls were less controllable during play. Neither study showed a linear relationship between spin control and spin data from an oblique racket impact. While further oblique impact work could be pursued to establish a relationship, player inconsistencies in determining differences make agreement unlikely. It is hypothesised that other information gathered during play affects player perceptions of spin control. Ball liveliness showed a relationship with racket COR for both the age and fuzz studies, though impact properties suggest a more promising area of work. While the studies showed similar agreement only for contact time, it is believed players were not finding differences in this but that other properties strongly related to contact time, like peak force \((r = -0.987)\), influenced player decisions. Haake et al. (2003) calculate ball stiffness from contact time using a single degree-of-freedom, viscoelastic model. Further work in improving the impact model used to determine stiffness values in this thesis could improve its relationship to perception data. Though fuzzy balls only showed a hardness relationship with impact properties on the serve, natural ageing results suggest good potential for both shots. Chapter 9 indicated good general player agreement on ball hardness. Neither study showed any agreement between impact properties and ball pleasantness. This is attributed to a lack of player consensus on pleasantness. Further oblique impact analysis is suggested for establishing a stronger relationship with bounce speed and bounce height as perceptions show some agreement with rigid plate COR.

### 10.3.2 Correlation with Measures of Ball Degradation

Nearly all of the perceived characteristics were strongly related to ball fuzziness, shown in Table 10.4, though bounce height was the only result related to ball age. Improved modelling of the nonlinear nature of pressure loss could improve the relationship with player perceptions. Significant correlations are again indicated in blue, and promising areas highlighted in red.

As bounce height produced no significant differences in perception for the age study, the other relationships related perceptible differences directly to differences in ball fuzziness. Flight speed suggests noticeable differences due to fuzziness of 2.01mm and 2.07mm for the forehand and serve. Liveliness and hardness on the serve indicate respective thresholds of approximately 2.53mm and 1.82mm. Ball weight indicated perceptible differences at 3.32mm for the forehand and bounce speed at 2.29mm on the serve. The threshold for perception of bounce height varied from 1.71mm for the forehand to 3.53mm on the
serve. As bounce properties were more noticeable during the forehand, it is expected that players struggled to identify differences during the serve and instead used other ball properties to determine bounce height.

### 10.4 Significant Areas of Player Feel and Perception

Areas of player perception showing strong agreement with ball testing data, along with information supporting strong areas of player perception gathered in Chapter 9, were used to determine important areas of perceived ball feel and performance. Selected areas will ideally relate to both fuzziness and natural ageing, though it is acknowledged that the ‘invisible’ difference of natural ageing is harder for players to identify. Kepner & Tregoe (1981) develop a systematic method of decision making involving a scoring matrix. By identifying and weighting desired objectives, alternative choices can be scored and the most suitable alternative selected. A similar method used six objective areas identified for the perception results to determine the most suitable areas of perception. They include good differentiation in merit values, consistency in responses, reliability between shots, general player agreement, and correlation with experimental ball data and measured ball characteristics. The first four areas were determined from player responses in Chapter 9 and the latter two from relationships examined in this chapter. Equal weighting was given to both player perception and experimental data, so values were averaged before computing the final score for each area of player perception.

Although data were collected for the forehand shot during testing, the improved results with the serve make it a more useful shot in future testing and for analysis. Matrix scoring, therefore, was based only on results from the serve in both the natural ageing and fuzz studies. Perception questions were scored a -1, 0, or +1 based on their strengths in player perception testing and relationship with dynamic test data and ball characteristics shown in Tables 10.3 and 10.4. Scoring for the player testing and experimental data was performed according to significant differences and correlations determined during testing. A score of 0 indicates significance in one study, while a score of +1 indicates significance in both studies. A -1 indicates that the question did not produce suitable results in either study. Positive results for relationships with dynamic experimental testing and ball degradation measures were given for significance above the 0.80 level. While this is a low level of significance, it does suggest some agreement in the data and a useful area for further work. Acceptable questions were those with scores greater than or equal to 0 as this indicated good agreement for at least half of the data in the two studies.

Table 10.5 shows the scoring matrix used to evaluate perceived ball properties. Results indicate five suitable questions for future player perception testing in evaluating perceived performance and feel characteristics of tennis balls: flight speed, hardness, liveliness, bounce speed, and bounce height. Ball weight showed promising results, but could not be consistently correlated with impact data for the studies. It is suggested that these questions be used in determining future play and feel preferences for tennis balls. By having players rate the importance and ideal level of each ball property, perceptions can be evaluated to determine balls with the most desired play and feel characteristics.
Table 10.5: Scoring matrix for areas of player perception.

<table>
<thead>
<tr>
<th>Perceived Property</th>
<th>Player Testing</th>
<th>Experimental Dynamic</th>
<th>Average Player</th>
<th>Average Exper</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Merit</td>
<td>Consist.</td>
<td>Reliab.</td>
<td>Agree</td>
<td>Ball</td>
</tr>
<tr>
<td>Flight speed</td>
<td>0</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td>Flight control</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Spin control</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Liveliness</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>Hardness</td>
<td>+1</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>Pleasantness</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Weight</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bounce speed</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bounce height</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
</tbody>
</table>

10.5 Summary of Evaluations

The relationships examined in this chapter offer insight into the complicated nature of ball feel. While five suitable areas of questioning were determined for evaluating perceived ball feel and performance differences, there are also indications that these alone will not fully characterise player perceptions. Ball aesthetics clearly play an important role in player psychology and objective test data cannot be assumed to suitably incorporate these factors. It is suggested that future investigations into ball feel utilise two simultaneous investigations with players. Use of a conjoint investigation incorporating ball fuzziness and logo condition, coupled with responses in the five areas of perception, could be used to assess the degree to which players are influenced by aesthetic ball attributes in their evaluations of feel and performance. With the relationships developed in this chapter, player perception evaluations can also incorporate dynamic ball test data. A summary of the minimum perceptible differences determined from significant relationships between perception data and experimental data is shown in Table 10.6. It is suggested that further testing with an increased number of samples could identify perceptible thresholds below these levels.

Table 10.6: Summary of perception thresholds.

<table>
<thead>
<tr>
<th>Perceived property</th>
<th>Significant difference caused by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight speed</td>
<td>$C_D$ (0.08), fuzziness (2.07mm)</td>
</tr>
<tr>
<td>Bounce speed</td>
<td>fuzziness (2.29mm)</td>
</tr>
<tr>
<td>Bounce height</td>
<td>fuzziness (1.71mm)</td>
</tr>
<tr>
<td>Liveliness</td>
<td>damping (1.50Ns/m^2), peak force (119N), fuzziness (2.53mm)</td>
</tr>
<tr>
<td>Hardness</td>
<td>damping (1.14Ns/m^2), peak force (85N), fuzziness (1.82mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>damping (2.39Ns/m^2), peak force (187N), fuzziness (3.32mm)</td>
</tr>
</tbody>
</table>

Findings from objective and subjective work show good relevance to manufacturers, governing bodies, and players by providing useful information to improve ball design, selection, and monitoring. The importance of ball aesthetics should be noted by manufacturers as both ball fuzziness and logo condition affect perceptions of ball playability. Player testing also indicated an interest in slightly balder tennis balls than currently manufactured. Standardised test results suggest that some balls will no longer meet standardised test requirements due to natural ageing after three weeks. The importance of ball fuzziness throughout all testing suggests that closer attention be given to rates of mass loss and changes to ball fuzziness with play. While no further regulations may be required, a better understanding of brand differences could provide useful information regarding play characteristics and acceptable levels of ball use. The importance of ball surface condition in performance and perception evaluations should also alert players to the importance of this ball component, as opposed to natural pressure loss, when selecting balls for play.
Chapter 11

Conclusions and Further Work

Work in this thesis was performed to address three major aims: develop a mechanism to assess tennis ball degradation, provide an appropriate objective assessment of tennis ball degradation, and provide an appropriate subjective assessment of ball degradation. Important findings and areas of further work are discussed below.

11.1 Conclusions

Several significant areas have emerged from work performed in this thesis. These achievements include a structure for future investigations and objective and subjective analyses of ball degradation. New analysis techniques used in this research are also discussed.

Mechanism for Future Investigations

This thesis provides a systematic assessment of ball degradation in three main areas: causes of wear and degradation, ball performance, and player perception. While further work inevitably exists in each of these areas, techniques and results for a substantial portion of work on ball wear degradation have been presented and provide a mechanism to structure future research in the areas of tennis degradation, ball performance, and player perception.

- Four levels of textile wear were identified and associated with tennis ball surface conditions: bald, new, loose fuzz, and tufted fuzz.
- Aesthetic differences in balls play a more important role in player perception than ‘invisible’ differences such as natural pressure loss.
- Five areas of perceived feel and performance showed good consistency in player responses and agreement with objective measures of ball condition. These include flight speed, hardness, liveliness, bounce speed, and bounce height.
- Sensory evaluation techniques were used successfully in a variety of applications. Methods incorporated complete and partial block rankings, paired comparisons, ratings of ball samples.
- Components of tennis ball degradation are examined in detail and important contributions, such as impact speed, noted. Ball fuzziness and natural ageing produced the most varied results during impact testing and were selected for player testing.

New Analysis Techniques

Several new techniques were incorporated into this thesis to provide efficient data analysis and gather perception information. The growing importance of digital imaging and the internet suggest techniques developed in these areas are particularly significant.
The digital fuzziness metric provides a new method for ball fuzziness measurement, shows good agreement with perception and aerodynamic data, and an ability to objectively characterise the surface condition of tennis balls.

Automated object tracking during COR processing eliminates inconsistencies found with human processing methods and object selection.

Internet based sensory evaluation techniques incorporate good experimental design and randomisation to gather information on tennis ball aesthetics.

Conjoint analysis identifies important product attributes and shows good potential for use in other areas of the sports industry, notably by manufacturers in optimising ball aesthetics.

**Objective Analysis**

Several areas of objective analysis of ball degradation were considered. Causes of tennis ball degradation were analysed with standardised tests and the digital fuzziness metric. Extensive impact testing was used to determine important degradation components that influence ball impact properties.

- No direct relationship was found between ball mass loss and fuzziness during wearing.
- Pressurised balls undergo the most rapid rate of pressure loss during the first thirty days after opening.
- A trajectory model incorporates spinning data to allow instantaneous force calculations and eliminate assumptions made by previous researchers. The model suggests differences in ball spin and velocity imparted during racket impacts may be more important in ball trajectory differences than drag forces.

**Subjective Analysis**

Subjective assessments of tennis ball degradation focused on ball aesthetics and perceived feel and performance properties. Both tactile and internet-based evaluations were used in examining ball aesthetics. Perceived feel and performance differences were assessed using naturally aged and fuzzy tennis balls during crosscourt forehand and service shots performed by experienced players.

- There is an optimal range of ball fuzziness, surrounding the condition of a new ball, that is preferred by players.
- Acceptability ratings may be used in place of ball preference rankings when assessing ball preferences for match play.
- Ball fuzziness, colour, and logo condition were identified as the three main components of tennis ball aesthetics. Ball fuzziness was nearly twice as important as the ball logo in determining ball playability. Colour was not a significant factor in player decisions.
- Player perceptions of ball aesthetics are linked to perceived ball play characteristics like flight control, stiffness, and weight. This makes ball aesthetics especially important in determining player perceptions of ball playability and manufacturing quality.
- Fuzzy balls and the service shot showed better differentiation and consistency in player responses. Both areas support the importance of visual and tactile ball attributes in player perception.

**11.2 Further Work**

Four main areas of further work were identified from the work and results presented in this thesis. Possible avenues of investigation are detailed below, along with their relationship to research already conducted.

**Performance Model**

The current trajectory model incorporates several areas of improved impact and flight parameters. It is suggested that further work be conducted to develop it as a performance model capable of accurately
simulating ball play characteristics. Further oblique court surface testing is needed to determine ball rebound, friction, and spin characteristics with a variety of inbound spin rates and ball conditions. In lieu of physical testing data, Cross (2003a, 2005) develops two models of ball impact and spin generation with court surfaces and tennis rackets. Further work could expand these models to include ball degradation attributes. Figure 11.1 shows theoretical ball velocities and spin rates for impacts with a tennis racket (Cross, 2005). Improvement of this model could lead to an understanding of any differing racket impact angles and movements required for worn tennis balls.

<table>
<thead>
<tr>
<th>Pre-collision</th>
<th>Post-collision</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image-url" alt="Diagram" /></td>
<td><img src="image-url" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 11.1: Ball-racket impact conditions (Cross, 2005).**

The spin decay model also requires validation, suggested through the use of high speed video and measurement at several points throughout ball flight. The model currently can simulate four types of balls. Further aerodynamic data for a range of ball roughnesses would allow users to determine performance characteristics by inputting a ball roughness and fuzz type. A suggestion is to relate the coefficients of the polynomial surface fit to the aerodynamic data with metric roughness values and fuzz types. Performance model verification is suggested with three-dimensional stereo imaging of the ball to provide positional trajectory measurements that can be compared with the simulations. This ball performance model could then be used in the development of new ball designs when provided with suitable test data.

**Wearing Process**

The general wearing process for sateen weave balls is described by the transitions from new, to loose, to tufted, to bald fuzz for sateen weave balls examined in this thesis. It is understood that differing manufacturers, weave patterns, and needle felt balls will have individual rates of wear and degradation. Player attitudes towards differing ball brands also varies greatly and is expected to alter their perceptions of physical ball degradation. Further investigation into varied rates of degradation and their relationship to player perception would provide interesting data on perceptions of brand quality and important considerations for manufacturers.
Digital Fuzziness Metric

Initial results suggest the digital fuzziness metric is easy to use and provides good agreement with aerodynamic and player perception data. To this point, however, only one user has performed evaluations of ball fuzziness. Wider use of the metric will introduce human error factors and necessary programming improvements. Varied ball types and wear conditions will also provide data to improve the relationship to both objective and subjective data.

It is also suggested the digital fuzziness metric be used in the development of a single ball degradation metric using weighted factor analysis to incorporate natural ageing and aesthetic factors. This metric could then be used to assess overall ball degradation and potentially aid the development of new specifications for ball degradation.

Laboratory and Perception Testing

Several areas of testing suggest interesting areas of further work. The development of the spin rig in the wind tunnel available for use at Loughborough University was accompanied with the fitting of the tunnel with particle image velocimetry (PIV) capabilities. PIV uses seeded fluid particles (smoke dispersed in the airflow) to measure velocities and movements of air around an object. Use with a spinning tennis ball could provide further information on the role of fibre length and stiffness, airspeed, and spin in ball aerodynamic characteristics and fibre orientation during play.

Work suggests the importance of the racket stringbed and ball interaction in determining overall ball trajectory characteristics. Further work could examine this interaction in more detail, detailing the role of fibre interaction with the strings, spin generation, and friction for worn balls and expanding on the impact models developed by Cottey (2002) and Cross (2005).

Testing performed in Chapters 9 and 10 provide some indication of thresholds of player perception for naturally aged and fuzzy tennis balls. Further work is suggested to determine other limitations in player perceptions of ball characteristics. These include limits on reaction time, the effects of varied ball trajectory on player movement and stroke completion, and comparison of ball properties with perceptions of ball playability.
Chapter 12

References


Mosteller, F. (1951). Remarks on the method of paired comparisons: i. the least squares solution assuming equal standard deviations and equal correlations. ii. the effect of an aberrant standard deviation when equal standard deviations and equal correlations are assumed. iii. a test of significance for paired comparisons when equal standard deviations and equal correlations are assumed. *Psychometrika*, 16, 3-9, 203-206,207-218.


Appendix A

Digital Fuzziness Metric User Guide

The digital fuzziness metric (DFM) is a new technique for objectively assessing tennis ball surface condition. The method to determine the $R_A$ roughness value in millimetres for an image is detailed below. Twelve images are averaged to determine the roughness value for a given ball sample. The starting screen is shown below.

System Calibration

Input the distance (in millimetres) depicted in the calibration image in the ‘Calibration (mm)’ box. Then click on  and select the calibration image using the dialog box. Select two endpoints for the calibration distance by double clicking on the desired image location.
Load Image

Press [Load Image] to load an image for processing. Choose the desired sample using the display box.

![Image Processing Interface]

Crop Image

Use [Crop] to select a rectangular region for processing and eliminate unneeded background area. The thresholded image is shown along with the original cropped region to aide in removing image noise. The computed threshold is displayed in the 'Threshold' box.

![Cropped Image Example]

Remove Image Noise

To remove image noise occurring outside the ball area, use the [Image Noise] button. With each button press, a rectangular area can be selected and filled with background pixels. If any portion of the ball is accidentally enclosed in this area, the image must be reloaded and processing begun again. The original ball image displayed in the upper right corner of the screen should be used as a reference to prevent fuzz from the ball's surface from being removed. Example rectangles are shown on the screen below.

![Noise Removal Example]

153
Compute Roughness Value

Click on Continue to apply the roughness algorithm to the image. The $R_A$ roughness is displayed in the 'Results' box. The code can also be customised to output ball centre points, the calibration value, and other image properties. Pressing Close will exit the program.
Appendix B

Digital Fuzziness Metric Coding

0001 function varargout = anotherone(varargin)
0002
0003 % Begin initialization code - DO NOT EDIT
0004 gui.Singleton = 1;
0005 gui.State = struct('gui.Name', mfilename, ...
0006 'gui.Singleton', gui.Singleton, ...
0007 'gui.OpeningFcn', @anotherone_OpeningFcn, ...
0008 'gui.OutputFcn', @anotherone_OutputFcn, ...
0009 'gui.LayoutFcn', [], ...
0010 'gui.Callback', []);
0011 if nargin && ischar(varargin{1})
0012 gui.State.gui.Callback = str2func(varargin{1});
0013 end
0014
0015 if nargin
0016 [varargout{1:nargout}] = gui.mainfcn(gui.State, varargin{:});
0017 else
0018 gui.mainfcn(gui.State, varargin{:});
0019 end
0020 % End initialization code - DO NOT EDIT
0021
0022 % --- Executes just before anotherone is made visible.
0023 function anotheroneOpeningFcn(hObject, eventdata, handles)
0024 % Choose default command line output for anotherone
0025 handles.output = hObject;
0026 handles.output = hObject;
0027 % Update handles structure
0028 guidata(hObject, handles);
0029 axes(handles.axes1)
0030 axis off
0031 axes(handles.axes2)
0032 axis off
0033
0034 % --- Outputs from this function are returned to the command line.
0035 function varargout = anotherone.OutputFcn(hObject, eventdata, handles)
0036 % Get default command line output from handles structure
0037 varargout{1} = handles.output;
0038
0039 %--------------------------------------------------------------
0040 %--------------------------------------------------------------
0041
0042 % Creates interactive text box that requires a specified distance in mm for
0043 % the calibration function. This data input must be performed before
0044 % using the calibrate function.
0045 function dist_Callback(hObject, eventdata, handles)
0046 val=str2double(get(handles.dist,'String'));
0047 if isnumeric(val)
0048 handles.conversion=val;
0049 else
0050 set(handles.dist,'String','error');
0051 end
0052 % Update handles structure
0053 guidata(hObject, handles);
0054
0055 % --- Executes during object creation, after setting all properties.
0056 function dist_CreateFcn(hObject, eventdata, handles)
0057 if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
0058 set(hObject,'BackgroundColor','white');
0059 end

155
%Performs first step of metric process. Uses an interactive gui to load a calibration image and stores the pixel-to-distance calibration factor.

% Executes on button press in calibrate.

function calibrate_Callback(hObject, eventdata, handles)

[file, pathname] = uigetfile('*.','Image');
buffer=p11d;

HANDLES.calib = imread(file);

axes(handles.axes1)
set(gca, 'DataAspectRatio', [1 1 1])
image(handles.calib)
axis off

xallow user to click two points on image corresponding to locations differing by a specified distance.

[x1,y1] = getpts;
[x2,y2] = getpts;

temp_dist = sqrt((x1-x2)^2 + (y1-y2)^2);
handles.factor = handles.conversion / temp_dist;

% Update handles structure
guidata(hObject, handles);

% Loads an image for processing.
% Executes on button press in load.

function load_Callback(hObject, eventdata, handles)

[file, pathname] = uigetfile('*.','Image');
buffer=p11d;

HANDLES.start = imread(file);

axes(handles.axes1)
set(gca, 'DataAspectRatio', [1 1 1])
image(handles.start)
axis off

axes(handles.axes2)
set(gca, 'DataAspectRatio', [1 1 1])
image(handles.start)
axis off

% Allows user to select a rectangle and crop the image. Image thresholding is performed at this step. Thresholding results are stored in a text box for the user to evaluate. This could also be output to the results file.

% Executes on button press in crop.

function crop_Callback(hObject, eventdata, handles)

RECT = getrect;

rl handle.s.xmin = round(RECT(1));
rl handle.s.xmax = round(RECT(1) + RECT(3));
rl handle.s.ymin = round(RECT(2));
rl handle.s.ymax = round(RECT(2) + RECT(4));
handles.ylength = handles.ymax - handles.ymin;
handles.xlength = handles.xmax - handles.xmin;
% creates greyscale image
handles.temp_image = rgb2gray(handles.start);
clear handles.grey;
clear handles.b;
for i = 1: handles.xlength
  for j = 1: handles.ylength
    temp = handles.temp_image(j + handles.ymin, i + handles.xmin);
    handles.grey(j, i) = temp;
  end
end
'1.fits normal distribution to pixels in greyscale image to determine image threshold
[counts, bins] = imhist(handles.grey);
[val, index] = max(counts(1:180));
g = 1;
while counts(g) == 0
  g = g + 1;
end
new_counts = counts(g:(2*index-g));
new_bins = bins(g:(2*index-g));
[mu, sigma] = normfit(new_bins, [], [], new_counts);
threshold determined from properties of normal distribution.
threshold = round(mu + 3*sigma) / 255;
%threshold threshold image into a black and white image and uses Matlab's edge detection algorithm to produce a ball outline.
set(handles.edit2, 'String', num2str(handles.threshold));
handles.b = im2bw(handles.grey, handles.threshold);
handles.b = bwperim(handles.b);
% Update handles structure
guidata(hObject, handles);
% cropped colour image and ball outline displayed in the two figure windows
axes(handles.axes2);
set(gca, 'DataAspectRatio', [1 1 1])
image(handles.start);
axis([handles.xmin handles.xmax handles.ymin handles.ymax]);
axis off
axes(handles.axes1);
set(gca, 'DataAspectRatio', [1 1 1])
image(handles.b•32);
axis off
% output text box for threshold to be displayed. A user can manually edit
%threshold by entering a value between 1-255.
val = str2double(get(handles.slider2, 'Min')) & val <= get(handles.slider2, 'Max')
handles.threshold = val / 255;
else
set(handles.edit2, 'String', 'error');
end
axes(handles.axes1);
set(gca, 'DataAspectRatio', [1 1 1])
image(handles.b•32);
axis off
% Execute during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
if ispc & isequal(get(hObject, 'BackgroundColor'), get(0, 'defaultUicontrolBackgroundColor'))
set(hObject, 'BackgroundColor', 'white');
end
0216 % Allows user to select errant pixels within a rectangular region that is
0217 % set to black. Can be performed multiple times.
0218 % Executes on button press in Black.
0219 function Black_Callback(hObject, eventdata, handles)
0220 rect = getrect;
0221 xmin = round(RECT(1));
0222 xmax = round(RECT(1) + RECT(3));
0223 ymin = round(RECT(2));
0224 ymax = round(RECT(2) + RECT(4));
0225 for i = xmin:xmax
0226     for j = ymin:ymax
0227         handles.b(i,j) = logical(0);
0228 end
0229 end
0230 guidata(hObject, handles);
0231 axes(handles.axes1)
0232 set(gca, 'DataAspectRatio', [1 1 1])
0233 image(handles.b*32)
0234 axis([0 handles.xlength 0 handles.ylength]);
0235 axis off
0236 % Update handles structure
0237 guidata(hObject, handles);
0238 axes(handles.axes1)
0239 % Performs algorithm calculations to determine ball roughness value.
0240 % Executes on button press in process.
0241 function process_Callback(hObject, eventdata, handles)
0242 rov_size = 0;
0243 col_size = 0;
0244 length = 0;
0245 % Determine ball center using center of mass technique
0246 bw = im2bw(handles.grey, handles.threshold);
0247 bw = bwareaopen(bw, 30);
0248 se = strel('disk', 3);
0249 bw = imclose(bw, se);
0250 bw = imfill(bw, 'holes');
0251 L = bwlabel(bw);
0252 stats = regionprops(L, 'Area', 'Centroid');
0253 allarea = [stats.Area];
0254 allcentroid = [stats.Centroid];
0255 [r, v] = size(allarea);
0256 for k = 1:v
0257     if stats(k).Area == max(allarea)
0258         centroid = stats(k).Centroid;
0259     end
0260 end
0261 handles.x_center = centroid(1);
0262 handles.y_center = centroid(2);
0263
0264 % Determines ball profile by selecting non-zero radii values. Converts
0265 % Xpixel locations to polar coordinates using ball centre.
0266 % Determines ball profile by selecting non-zero radii values. Converts
0267 % Xpixel locations to polar coordinates using ball centre.
0268 for f = 1:handles.c
0269     dist(f) = 0;
0270 end
0271 for i = 1:handles.ylength
0272     for j = 1:handles.xlength
0273         if double(handles.b(i,j)) == 1
0274             y = handles.y_center - i;
0275             x = handles.x_center - j;
0276             radius = sqrt(x^2 + y^2);
0277             if x > 0
0278                 theta = atan(y/x);
0279             else
0280                 theta = theta + pi;
0281             end
0282             % Normalize and adjust quadrants
0283             if x < 0
0284                 theta = theta + pi;
0285             end
0286         end
0287     end
0288 end
0289
0290
0291
158
if y <=0
theta = theta + 2*pi;
end
%normalizes with theta across bottom to create array
th = round((theta*handles.c / (2 * pi)));
if th=0
if radius > dist(th)
dist(th)= radius;
end
end
end
end if
%normalizes with theta across bottom to create array
th = round(theta •handl es . c
I(2 * pi));
end
end
end
end
end
end
end
end
if th-=0
end
end radius > dist(th)
dist(th)= radius ;
end
end 'l.c r eates pr ofile from non-zero values.
end
end
t=1;
for g=1:handles.c-1
if dist(g) -=0
dista(t)=dist(g);
t=t+1;
end
end
profile = dista;
end
%fit peaks with zero degree polynomial (straight horizontal line)
[temp1,temp2] = size(profile);
col = linspace(1,temp2,temp2);
meanline = polyfit(col, profile,0);
profile2=abs(profile-meanline);
Ra=sum(profile2)/temp2;
% converts pixel measurement to mm.
Ra=Ra•handles.factor;
varargout=[Ra,handles.factor]
set(handles.resultbox,'String',num2str(varargout));
end
% Update handles structure
guidata(hObject, handles);
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
% Output results to a textbox.
function resultbox_Callback(hObject, eventdata, handles)
function resultbox_CreateFcn(hObject, eventdata, handles)
if ispc & isequal(get(hObject, 'BackgroundColor' ) ,get(O,'defaultUicontrolBackgroundColor' )
set(hObject, 'BackgroundColor', 'white');
end
end
end
end
end
end
end
end
end
end
end
end
% Executes on button press in close.
function close_Callback(hObject, eventdata, handles)
end
end
Appendix C

Statistical Techniques

Complete Block Analysis for Ranks

Using a randomised complete block design, the Friedman-type statistic, \( T \), is used with the \( \chi^2 \) distribution to determine ranking significance. The \( \chi^2 \) distribution is used because of its close association with a normal distribution. If the rankings are significant, a multiple comparison procedure can then be used to determine significant differences between individual samples. Initial statistical analysis relies on the use of the rank sum (total of individual ranks) for each sample. Significant differences are determined according to Fisher’s Least Significant Difference (LSD). This value depends on the number of samples, \( n \), the number of panellists, \( N \), and the individual rank values, \( v \). Equations used in the analysis are given in Equations C.1 and C.2 (Meligaard et al., 1999):

\[
T = \left( \frac{12}{Nn(n+1)} \sum_{i=1}^{N} v_i^2 \right) - 3N(n+1) \quad \text{where } v_j = \sum_{i=1}^{N} v_{ij} \tag{C.1}
\]

\[
\text{LSD} = t_{n/2,\infty} \sqrt{\frac{Nn(n+1)}{6}} \tag{C.2}
\]

The Kendall coefficient of concordance, \( W \), determines the similarity between several sets of rankings, with significance for \( N > 7 \) determined by the \( \chi^2 \) distribution, shown in Equations C.3 and C.4 (Siegel & Castellan, 1988). The coefficient of concordance, where \( \bar{R}_j \) is equal to the average rank for each sample and \( \bar{R} \) equals the average of all ranks, ranges from 0 to 1, with higher values indicating that the panellists are ranking the objects on similar standards.

\[
W = \frac{1}{N} \sum_{j=1}^{N} (\bar{R}_j - \bar{R}) \tag{C.3}
\]

\[
\chi^2 = N(n-1)W \tag{C.4}
\]

Cronbach’s Alpha

Cronbach’s alpha (\( \alpha_c \)) is a measure of the internal consistency reliability of a set of survey results. It assesses the correlation between observed scores on a conceptual scale and the underlying concept the scores are designed to measure. Low values indicate that the scale did not adequately assess the desired attribute. This reliability is a function of the number of test items (\( n \)) and the average inter-correlation among the items (\( \bar{r} \)), shown in Equation C.5. It ranges from 0 to 1, with values above 0.70 considered to be reliable (Hays, 1988; Nunnally & Bernstein, 1994).

\[
\alpha_c = \frac{n \cdot \bar{r}}{1 + (n-1) \cdot \bar{r}} \tag{C.5}
\]

Goodness of fit

Goodness of fit (\( R^2 \)) refers to the statistical resemblance of a model to measured data. It is the ability of a model to predict dependent variables from the independent variable in a set of data. The magnitude ranges from zero to one, with higher values indicating better fit. A \( R^2 \) value of zero for a linear model indicates a horizontal line passing through the mean of all measured values and a poor model fit. A value of one indicates points lie directly on a curve and dependent variables can be predicted from the independent variable in the model.

Incomplete Block Analysis for Ranks

Durbin (1951) presents a thorough analysis of rank data gathered from a balanced incomplete block design. A balanced incomplete block design requires that each object (\( n \)) should be ranked an equal number of times (\( m \)) in the experiment and that each pair of objects should be observed the same number of times (\( \lambda \)). After calculating the coefficient of concordance
for the design, a further test is required to determine the significance of the rankings. Using the Beta distribution and Equation C.6, Fisher’s variance ratio distribution can be determined using $\nu_1 = 2q_1$ and $\nu_2 = 2q_2$ degrees of freedom, as calculated from Equations C.7 and C.8.

$$F_r = \frac{W\left(\frac{\lambda(n+1)}{k+1} - 1\right)}{1 - W}$$  \hspace{1cm} (C.6)

$$q_1 = mn\left(1 - \frac{k+1}{\lambda(n+1)}\right) - \frac{k+1}{\lambda(n+1)}$$  \hspace{1cm} (C.7)

$$q_2 = \left(\frac{\lambda(n+1)}{k+1} - 1\right)\rho$$  \hspace{1cm} (C.8)

**Kendall’s Coefficient of Agreement for Paired Comparisons**

Kendall’s coefficient of agreement, shown in Equation C.9, is used to assess agreement between subject responses $(a_{ij})$ during paired comparison testing for $t$ objects and $N$ subjects (Kendall & Babington Smith, 1940). The Friedman statistic, shown in Equation C.10, is calculated from the rank sums in each preference matrix and evaluated according to a critical value determined from the $\chi^2$ distribution. For $t = 4$ and $\alpha = 0.050$, this critical value is $T = 7.81$.

$$T = \frac{4 \sum_{i=1}^{4} \sum_{j=1}^{t} a_{ij}(a_{ij} - 1)}{t(t-1)N(N-1)} - 1$$  \hspace{1cm} (C.9)

$$T = \left[\frac{4}{N^2} \sum_{j=1}^{t} R_j^2\right] - 9N(t-1)^2$$  \hspace{1cm} (C.10)

**Multiple Comparison Procedures**

When data is collected for several variables, multiple comparison procedures are used to determine if a significant difference exists in between the sample means. If treatment pairs were individually compared, the chance that one of the comparisons will be significant is much greater than a stated significance level. Multiple comparison procedures look to minimise the chance of a Type I error, or the likelihood that differences occur due to chance (due to variations in sampling and measurement). If a significant difference is found between treatments, post hoc tests can be used to determine significant differences between individual treatment pairs.

A standard two-way ANOVA looks to identify a source of variability with a group of data and determine if variation is due to main or interaction effects. Significance is determined according to Fisher’s F-distribution. Two main assumptions must be met when performing an ANOVA: homogeneity of variance and random sample selection. These ensure that samples are randomly selected from a given population and that all treatments have the same standard deviation. Additionally, it is assumed that measurements are taken from a normally distributed population with measurements taken on an equal interval scale.

Friedman’s test is a nonparametric test similar to a balanced two-way ANOVA, but tests only for column effects after adjusting for possible row effects. Friedman’s test is appropriate when columns represent treatments under study, and rows represent blocks that need to be taken into account but are not of any interest. It does not test for row effects or interaction effects. Because it is a non-parametric test, it is free from the assumptions associated with an ANOVA analysis that relies on an equal interval scale of measurement and a normal distribution. It is often used for rank data.

If a significant value is obtained using a multiple comparison procedure, post-hoc analysis is used to determine significant differences between treatment means. Tukey’s Honestly Significant Difference (HSD) test is one of the most widely used tests in the behavioural sciences, though it can be overly cautious and prevent all comparisons from being made. Fisher’s Least Significant Difference (LSD) uses a t-test to compare all possible means to determine significant differences only after an F-ratio test establishes significance between means. The selection of a method was determined by the technique most commonly used for a given experimental design in the literature (ratings, rankings, data means, paired comparisons, complete or partial blocks).

**Pearson Correlation Coefficient**

This correlation is a parametric measure of association between two continuous, random variables. It assumes there is a linear relationship and is non-dimensional so the fits from different data sets can be compared. The correlation ranges from +1 to −1, with a value of 0 indicating there is no linear relationship between the variables.

The calculation of this value for known data sets $x_1$ and $x_2$, where $x_1$ and $x_2$ are sample means, is shown in Equation C.11. This equation is the equivalent to dividing the covariance between $x_1$ and $x_2$ by the product of their standard deviations. Significance was determined using Pearson’s table of critical values, shown in Table C.1 for $\alpha = 0.05$ for $N_f$ degrees of freedom, where $N_f$ is two less than the number of sample pairs.
Silhouette Statistic

The silhouette statistic is a measure of how close each point in one cluster is to neighbouring groups for k-means clustering (Rousseeuw, 1987). It ranges from +1 to −1. High values indicate good separation, while negative values indicate some points may be improperly assigned to clusters. A value of zero indicates no distinct cluster separation.

If $a(s_i)$ is the average dissimilarity of $s_i$ to all points in its own cluster and $b(s_i)$ denotes the average dissimilarity to the second best cluster for $s_i$, the silhouette statistic for a single point is given by Equation (C.12). The measure for the quality of the entire clustering process is given by the average silhouette value ($s$) for all points shown in Equation (C.13).

$$ r = \frac{\sum (x_1 - \bar{x}_1)(x_2 - \bar{x}_2)}{\sqrt{\sum (x_1 - \bar{x}_1)^2 \sum (x_2 - \bar{x}_2)^2}} \tag{C.11} $$

$$ \text{sil}(s_i) = \frac{b(s_i) - a(s_i)}{\max[a(s_i), b(s_i)]} \tag{C.12} $$

$$ s = \frac{1}{k_c} \sum_{s_i \in S} \text{sil}(s_i) \tag{C.13} $$

Spearman Rank Order Correlation

Spearman's rank order correlation, $r_s$, is a non-parametric measure of association based on the ranks of data values. Data analysed by this method must be measured at least on an ordinal scale so it can be ranked in an ordered series, though it no assumptions are made concerning the distribution of the data.

Calculation is performed as shown in Equation (C.14), where $d_i$ is the difference in ranks between object pairs and $N_p$ is number of object pairs. This coefficient can also be adjusted for tied ranks within samples (Siegel & Castellan, 1988).

$$ r_s = 1 - \frac{6 \sum d_i^2}{N_p (N_p^3 - N_p)} \tag{C.14} $$

Table C.1: Pearson’s table for critical values of $r$.

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<thead>
<tr>
<th>$N_f$</th>
<th>0.05</th>
<th>0.025</th>
<th>0.005</th>
<th>0.0005</th>
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<tr>
<td>One-tailed probabilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.900</td>
<td>0.950</td>
<td>0.990</td>
<td>0.999</td>
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<td>5</td>
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<td>0.878</td>
<td>0.959</td>
<td>0.991</td>
</tr>
<tr>
<td>6</td>
<td>0.729</td>
<td>0.811</td>
<td>0.917</td>
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<tr>
<td>7</td>
<td>0.669</td>
<td>0.754</td>
<td>0.875</td>
<td>0.951</td>
</tr>
<tr>
<td>8</td>
<td>0.621</td>
<td>0.707</td>
<td>0.834</td>
<td>0.925</td>
</tr>
<tr>
<td>9</td>
<td>0.582</td>
<td>0.666</td>
<td>0.798</td>
<td>0.898</td>
</tr>
<tr>
<td>10</td>
<td>0.549</td>
<td>0.632</td>
<td>0.765</td>
<td>0.872</td>
</tr>
<tr>
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<td>0.521</td>
<td>0.602</td>
<td>0.735</td>
<td>0.847</td>
</tr>
<tr>
<td>12</td>
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<td>0.576</td>
<td>0.708</td>
<td>0.823</td>
</tr>
<tr>
<td>13</td>
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<td>0.553</td>
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<td>0.801</td>
</tr>
<tr>
<td>14</td>
<td>0.458</td>
<td>0.532</td>
<td>0.661</td>
<td>0.780</td>
</tr>
<tr>
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<td>0.441</td>
<td>0.514</td>
<td>0.641</td>
<td>0.760</td>
</tr>
<tr>
<td>Two-tailed probabilities</td>
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<td></td>
<td></td>
</tr>
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<td>0.05</td>
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<tr>
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<td>0.684</td>
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<td>0.780</td>
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<tr>
<td>15</td>
<td>0.441</td>
<td>0.514</td>
<td>0.641</td>
<td>0.760</td>
</tr>
</tbody>
</table>
Appendix D

Internet Surveys

Metric Validation Survey

Ball Wear Survey

Thank you for participating in this survey for my research. I am a PhD student at Loughborough University investigating the causes of tennis ball wear, and the resulting effects on ball performance and player perception. The condition of the ball's cloth cover plays an important role in how players assess the wear sustained by a ball, as well as performance characteristics like ball aerodynamics. For more information about my research, please feel free to contact me or visit the Sports Technology Research Group for other sports related research performed at Loughborough.

For this survey, you will be presented with four balls at a time that I would like you to rank from fuzzy to bald with 1 representing the fuzziest sample and 4 representing the baldest sample. No ties are allowed.

Many thanks,

Carolyn Steele
C.Steele@lboro.ac.uk

<table>
<thead>
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<th>Name (optional)</th>
<th></th>
</tr>
</thead>
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<tr>
<td>Coaching Qualifications</td>
<td></td>
</tr>
<tr>
<td>Frequency of Play</td>
<td>Daily</td>
</tr>
<tr>
<td>Experience (years)</td>
<td></td>
</tr>
</tbody>
</table>

Figure D.1: Introductory page.
Figure D.2: Block 1.

Figure D.3: Block 2.
Figure D.4: Block 3.

Figure D.5: Block 4.
Figure D.6: Block 5.

Figure D.7: Block 6.
Figure D.8: Block 7.

Figure D.9: Block 8.
Figure D.10: Block 9.

Figure D.11: Block 10.
Figure D.12: Block 11.

Figure D.13: Block 12.
Figure D.14: Block 13.

Figure D.15: Block 14.
Figure D.16: Block 15.

Figure D.17: Block 16.
Figure D.18: Block 17.

Figure D.19: Block 18.
Figure D.20: Block 19.

Figure D.21: Block 20.
Ball Aesthetics Survey

Figure D.22: Ball samples developed for conjoint analysis investigation in Chapter 8.
Appendix E

Impact Testing: Equipment Specifications

Two testing setups were used in collecting impact data. The first utilised a pneumatic ball cannon to fire balls into an enclosed test chamber, shown in Figure E.1. These impacts utilised high speed imaging equipment and signal collection systems. A Berkeley Nucleonics 10 channel pulse generation unit was used to control the timing of a high speed camera, acceleration plate data collection, and Sensicam system during laboratory testing. Pulse generation was triggered, with an appropriate delay, by the passage of the ball through the first light gate. Court impacts were recorded with a Sestée court pace measurement system.

Cannon

The pneumatic air cannon utilises compressed air between 20-80psi to fire balls at speeds up to 66 ms⁻¹ into an enclosed test chamber. The barrel was 1m long with an internal diameter of 70mm for use with Type I and II balls. The barrel end was positioned 0.8m from the contact surface.

The enclosure, shown in Figure E.1, includes a rigidly mounted fixture capable of impact angles between 5° and 90°. The fixture was sufficiently large and rigid to eliminate rig movement during impact. A laser pointer was positioned along the central axis of the cannon barrel to determine the exact location of impact and rig alignment. A digital inclinometer calculated the accuracy of the target to the nearest 0.1°. Two ballistic light gates, 195mm apart, were positioned directly next to the barrel aperture and connected to an electronic counter to calculate incoming ball speeds.

Figure E.1: Adjustable frame in cannon enclosure
Imaging Equipment

Two imaging systems were used in recording impacts. The Sensicam system superimposes multiple images captured during an impact, while the high speed system produces digital video files composed of individual image frames. Both systems were found to have speed accuracy errors of less than 4% when compared with electronic counter measurements.

Sensicam System

The Sensicam camera electronically samples up to ten still images and transfers them to a computer using a fibre optic cable. Specialised software allows for fine control of the timing, number, and length of exposures. The time interval between images was set at 4ms with exposure times of 50μs. The images are combined, as in Figure E.2, to produce one image of ball rebound. With any application of high speed imaging, adequate lighting is crucial to producing useful images. To avoid overheating the chamber with constant, high-intensity lighting, a long duration (10ms), high intensity flash was triggered by the digital pulse generator. During this flash exposure, three images could be captured with sufficient lighting. A 100mm x 100mm grid was used as a calibration image in the plane of the ball’s trajectory. Ball locations were digitised and analysed to produce velocity, spin, and angle of projection values for each impact using the previously developed Flightpath software (Cotney, 2002).

Figure E.2: An example image taken from the Sensicam system.

Individual ball images were calibrated by marking an outer rectangle around the ball, in which a circle was inscribed. A trajectory line, calculated by joining the centre of each of the balls, determined ball launch angle and velocity. Spin was calculated by locating digitised lines passing through the ball centres. The angle differences between the lines, combined with the time between the images, was used to determine spin rates. The accuracy of the software and repeatability of results were examined by repeated processing of random image samples and by using a calibrated standard image with known velocity (44.7ms⁻¹), launch angle (30°), and spin rate (3000rpm). With regards to a standardised calibration image, processing results produced spin and velocity differences of less than 1.5%, and launch angle differences of less than 0.5%. To evaluate inherent errors due to system calibration and human processing, sample images were repeatedly calibrated and processed to determine variations in the results. COR and spin values for an image differed by less than 1% with these repetitions.

High Speed Camera

A Photron Fastcam Ultima APX high speed digital camera, set up perpendicular to impact, was also used in examining ball impacts. Though capable of running up to 100,000 frames per second (fps), a frame rate of 2,000fps provided manageable data capture and file sizes, with a resolution up to 1024x512 pixels. Standard shutter speeds are the inverse of the frame rate, though for this application the shutter speed was increased to 1/10,000 second to improve image clarity and ball tracking at high speeds. Twin halogen lights were mounted near the enclosure to enhance image quality and contrast.

An automated method of ball tracking was developed to eliminate sources of human error from data processing involving several thousand individual images. The cannon enclosure was lined with black paper to highlight the ball for easy segmentation. With the camera position fixed and consistent lighting, image sequences were automatically cropped, contrast enhanced, and thresholded to produce binary images. From these binary images, a particle tracking algorithm was used in conjunction with the Java-based program ImageJ. ImageJ is an open-source, image processing software developed for the medical industry with the potential to record macros, track and measure objects, incorporate calibration factors, and utilise user-developed functions (National Institute of Health, 2005). Examples of video frames and the detected ball are shown in Figure E.3.

Ball centroid position was recorded in each frame and saved to a text file. The ball height was constant during both the inbound and outbound phases of the normal impacts, so only the horizontal component of the ball position was processed. Centroid positions were read into MATLAB and plotted according to their position as shown in Figure E.4. Ball inbound velocity is given by the slope of the initial downward portion of the curve and the outbound velocity given by the upward
portion. The coefficient of restitution can be calculated from the ratio of these two values. To find a best fit slope for each velocity, points were selected at the beginning and end of each linear portion of the curve. A line fit to these points produced the slopes used to calculate the COR for each impact.

This method is seen as an improvement over manual tracking methods in high speed video as more frames are used in the analysis that produced variations in COR values of up to 5% during repeated processing. A minimum particle size was also set to eliminate the system tracking noise in the images. Any irregularly processed files could be detected, and individually analysed, when ball locations were plotted.

**Force Data**

Previous work has utilised a Kistler force transducer to measure ball impacts over a range of ball speeds (Davies, 2005). This method produced adequate force impact data to estimate ball stiffness and damping parameters using a single degree of freedom, viscoelastic model. Much of this plate, however, was made out of aluminum and there was no method to secure reference accelerometers. Improvements were attempted by Turner (2005) by developing a steel mounting for the transducer and incorporating threaded studs for fixing accelerometers. Despite precautions, results indicated large vibrations within the plate that did not produce acceptable data for analysis. Differences in the two plates are shown in Figure E.5.

A new method of measuring force during ball impacts, similar to one used to calibrate impact hammers, was devised as a solution to this problem. By measuring the acceleration of a freely suspended plate and using Newton’s Second Law of Motion \( F = ma \), the force during impact can be calculated. Several design specifications were developed by Turner (2005) in determining the final acceleration plate implementation, shown in Figure E.6.

- The plate must be of sufficient size such that the ball is in contact with the face at all points during impact.
- Bungees used to suspend the plate should not be extended to double their initial length, and must be able to be calibrated.
- Accelerometers should be positioned to measure acceleration parallel to the x, y, and z axes, and rotational accelerations about these axes.
- The system should provide improved force measurements and withstand repeated high speed impacts.

![Image processing sequence for automatic object detection.](image)

**Figure E.3:** Image processing sequence for automatic object detection.

![Plot of ball centre for a normal impact.](image)

**Figure E.4:** Plot of ball centre for a normal impact.
Bungee Calibration and Limitations

The total force produced by the ball during impact is given by a combination of plate acceleration and the bungees. While the mass and acceleration of the plate can be measured, the effects of the bungees must be calculated. The entire system can be described by Equation E.1.

\[ F_{\text{impact}} = m_{\text{plate}} x_{\text{plate}} + 8k_{a}x \]

(E.1)

At any point during the impact, the displacement of the plate is given by \( x_{\text{plate}} = \frac{1}{2} x_{\text{plate}} \Delta t \). Calculations indicate minimal plate displacement and a maximum force contribution by the bungees of approximately 1N at any point during impact. As the force levels were significantly larger than this, the bungee contribution to the system was ignored. This relationship can be confirmed through the use of the conservation of momentum equation shown in Equation E.2.

\[ m_{\text{ball,in}} v_{\text{ball,in}} = m_{\text{ball,out}} v_{\text{ball,out}} + m_{\text{plate}} v_{\text{plate}} \]

(E.2)

Measurements were made by integrating the plate acceleration data and tracking the ball using high speed video. Experimental results lead to momentum differences of less than 5\% and affirm that the system gives acceptable results.

Data Collection and Processing

Two Brüel and Kjær 4375V miniature piezoelectric charge accelerometers were attached with threaded studs to the acceleration plate. All signals were passed through a Nexus conditioning amplifier to a Hewlett-Packard 8-channel signal analyser. Data was recorded using SignalCalc 620 data processing software.

Six accelerometer locations were identified to measure rotational and translational acceleration for all three axes. For oblique impacts, measurements at all six locations would be required. Normal impacts, however, require only measurements from \( A_{1} \) and \( A_{2} \) (see Figure E.7) to assess the translational acceleration of the block, providing the ball impacts the plate between \( A_{1} \) and \( A_{2} \). Ball impact locations were monitored using a high speed camera and aligned using a laser. Block acceleration was calculated by averaging the results from \( A_{1} \) and \( A_{2} \).

Incorporating the mass of the plate (\( m_{\text{plate}} = 4.5375\text{kg} \)), the force profile for the impact can be determined according to Equation E.1, with the bungee contribution deemed negligible. Initial testing of the acceleration plate over a range of impact speeds produced similar force curves and peak values to those documented by Davies (2005) (Turner, 2005). The new force curves also show improved results as they contain much less noise than previous attempts shown in Figure E.5.
Sestée Machine

The Wassing Sestée has been developed to evaluate court surface pace by determining the coefficient of friction and the coefficient of restitution for a given ball and surface interaction. A diagram of the testing setup is shown in Figure E.8. Horizontal and vertical inbound and outbound velocities are measured to an accuracy of ±0.005ms⁻¹. Video analysis ensured the balls were initially projected with spin rates less than 180rpm and the inbound angle was not more than 16°.

Three properties were assessed from court surface testing: horizontal and vertical COR and the coefficient of friction. All measurements were calculated from the horizontal and vertical velocity data measured by the Sestée machine. The coefficient of sliding friction was calculated according to Equation E.3.

\[
\mu_f = \frac{V_{fx} - V_{jx}}{(1 + e_y)V_{iy}}
\]  

(E.3)
### DATA SHEET

**SUBJECT NUMBER:**

**SHOT SCORES**

<table>
<thead>
<tr>
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<th>Comparison 2</th>
<th>Comparison 3</th>
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<td>1 2 3 4 5 6</td>
<td>1 2 3 4 5 6</td>
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**Forehand**

**Serve**

**COMPAARED TO THE FIRST BALL,**

<table>
<thead>
<tr>
<th></th>
<th>FOREHAND</th>
<th>SERVE</th>
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<tbody>
<tr>
<td>the flight of the second ball was</td>
<td>more controllable</td>
<td>less controllable</td>
</tr>
<tr>
<td>the spin of the second ball was</td>
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</tr>
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<td>the second ball travelled</td>
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<td>the second ball bounced</td>
<td>higher lower</td>
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</tr>
<tr>
<td>the second ball felt</td>
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</tr>
<tr>
<td>the second ball came off the racket face</td>
<td>slower (deader) quicker (livelier)</td>
<td></td>
</tr>
<tr>
<td>the second ball</td>
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**Player Perception of Feel and Performance**

**Appendix F**
Player Perception of Ball Aesthetics

Tennis Ball Degradation Evaluation

Name (optional):
Ranking or Standard:
Age:
Years Playing Tennis:

Overview of study:
Much recent work has been directed towards understanding factors important in tennis ball feel and performance. This work has concentrated on measurable factors such as impact properties and aerodynamics. There is no current method to classify the appearance of a tennis ball other than through visual evaluations. It is not known how player perception of ball appearance relates to ball performance measures.

Please rank the balls in order of playing preference, with balls you would most like to play with at the top of the ranking. Once the final order is established, please also remark on whether you feel the ball is acceptable for match play based on its appearance.

<table>
<thead>
<tr>
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<tbody>
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</tbody>
</table>

Why did you feel Ball X was the best for play?

Why is Ball Y the worst for play?

What factors did you use to rank the balls?
Please rank the balls in order of fuzziest to least fuzz based on their appearance, with balls appearing the fuzziest appearing at the top of the ranking. Once the final order is established, please also remark on whether you feel the ball is acceptable for match play.

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<td>Acceptable for play:</td>
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<td>Acceptable for play:</td>
<td>Yes</td>
<td>No</td>
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</tbody>
</table>

What ball play properties do you determine from the appearance of a ball?

Do you have any other comments concerning ball wear or appearance that could be helpful in our research?