Important performance characteristics in elite grass court tennis: implications for practice

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Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.

2. None of the material contained in the thesis has been used in any other submission for an academic award.

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Abstract

Notational analysis has become a valued discipline and well-established tool in many sports. Historically, however, notational analysis and its potential for enhancing competitive performance have not been optimised in tennis, with a lack of grass court tennis research and associated practical applications particularly apparent. Additionally, tennis coaches have shown resistance towards technological advancements and are often unsure how to exploit the performance data available to them. In this thesis, a new, user-friendly data analysis method (*Percentage of matches in which the Winner Outscored the Loser*, PWOL) is developed and validated, to encourage tennis coaches to engage with notational analysis. The method is applied to Wimbledon match-play data, to identify the important performance characteristics in men's and women's elite grass court tennis. *Points won of 0-4 shot rally length* (i.e. short points) is revealed as the most important, so this characteristic is explored further, revealing the critical importance of serving and returning strategies. Accordingly, players' tactical serving and returning behaviours are examined using Hawk-Eye ball-tracking data, with results highlighting that players tend to use first serves to put opponents under positional pressure by aiming for lateral areas of the service box, while opting for safer second serve strategies, typically targeting more central areas. Male winning players were also able to use their serves and serve-returns to force opponents out of position more often than losing players, hitting a comparatively higher percentage of serves and serve-returns to lateral areas of the court.

Alongside the novel data analysis method, this thesis advances knowledge around the important aspects of grass court tennis match-play and provides insight into how matches are won at Wimbledon. Designed to inform practice, the practical application facilitates coaches aiming to develop evidence-informed practices for players during the grass court season, ensuring their training is representative of match-play. Implications for performance analysts and high-performance centres are also explored, to promote a more interdisciplinary approach to player development.

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Research Outputs

Peer-reviewed journal articles

Fitzpatrick, A., Stone, J. A., Choppin, S. and Kelley, J. (2019a). A simple new method for identifying performance characteristics associated with success in elite tennis. *International Journal of Sports Science and Coaching, 14*(1), 43-50.

Fitzpatrick, A., Stone, J. A., Choppin, S. and Kelley, J. (2019b). Important performance characteristics in elite clay and grass court tennis match-play. *International Journal of Performance Analysis in Sport, 19*(6), 942-952.

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Presentations

Fitzpatrick, A. (2018). *Can British tennis players train 'smarter' to increase their chances of success at Wimbledon?* Presentation, National Tennis Centre, London, UK.

Fitzpatrick, A. (2019). *Parameters related to success in elite grass court tennis: what should we coach?* Presentation, Sheffield Hallam University SPARC Seminar Series, Sheffield, UK.

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ANOVA	Analysis of Variance
ATP	Association of Tennis Professionals
BBC	British Broadcasting Corporation
CI	Confidence interval
GPS	Global Positioning System
IBM	International Business Machines
ITF	International Tennis Federation
k	Cohen's kappa
km/h	Kilometres per hour
LTA	Lawn Tennis Association
η^2	Eta-squared
PWOL	Percentage of matches in which the Winner Outscored the Loser
r	Pearson's correlation coefficient
r_{pb}	Point-biserial correlation coefficient
r_s	Spearman's rank-order correlation coefficient
sd	Standard deviation
WTA	Women's Tennis Association
χ^2	Chi-square

Chapter 1

Introduction and Thesis Structure

1.1. Introduction

In 1874, ‘sphairistike’ or ‘lawn tennis’ was heralded by The London Court Journal as a new sport, expected to replace ‘tired’ croquet as England’s leisure activity, due to its novelty and excitement (Wilson, 2014). Its rapidly increasing popularity led to the All England Croquet Club (later the All England Lawn Tennis and Croquet Club) hosting its first tennis tournament in 1877. The annual event, now known as The Championships at Wimbledon, is deemed by many to be the world’s most prestigious tennis tournament (Barrett, 2013). The growing status of tennis, its increasing international media coverage, and the introduction of the Davis Cup drew the world’s best players into the public eye in the early 20th century, leading to several players signing professional contracts (Eaves & Lake, 2018).

Spearheaded by Wimbledon, the ‘open era’ of tennis began in 1968, when Grand Slam tournaments first allowed professional players to compete alongside amateurs, who had previously resorted to collecting ‘under-the-table’ appearance fees (Jefferys, 2009). By the late 1970s, tennis had become a ‘big money’ sport, in which considerable prize money offerings could be supplemented, and in some cases surpassed, by players’ lucrative endorsement and sponsorship deals (Lake, 2019). In 1988, tennis became an Olympic Sport (for the second time), prompting many countries to vastly increase their financial investment into high-performance tennis and mass participation (Smolianov et al., 2015). Now one of the most popular sports globally (Martin & Martinez, 2014), tennis offers social and competitive opportunities for all ages, genders and abilities.

In line with the growth, professionalisation and commercialisation of tennis, its appeal and value as a research topic also increased. Advances in the physical strength and endurance, technical ability and tactical adaptability of players in the modern game led to the emergence of talent identification, coaching, and physical conditioning as widely recognised professions and vital aspects of player development (Lake, 2019). In turn, as observed in many sports (Duncan & Strudwick 2017; Moran & Toner, 2017), tennis players, coaches and high-performance centres begun to explore sport science disciplines in their quest to optimise performance and gain a competitive edge over others. Scientific support and research are particularly pertinent for tennis national governing bodies around the world, due to their considerable financial investment in junior development and elite performance programmes. Accordingly, Great Britain's Lawn Tennis Association part-funded the work in this thesis, with the aim of better informing their coaching practices, with particular emphasis on enhancing players' grass court development and match-play performances.

1.2. Thesis structure

This thesis examines elite men's and women's Wimbledon match-play and contextually interprets the results to provide practical recommendations to help coaches improve the specificity of their players' grass court season training. **Chapter 1** introduces tennis and provides a brief overview of its history. **Chapter 2** reviews notational analysis literature in tennis, highlighting several associated issues, and outlines the theoretical concepts that underpin the work presented in the thesis; this culminates in the aim and objectives. In **Chapter 3**, a simple new data analysis method for identifying important performance characteristics in elite tennis is proposed and validated against two previously used statistical methods. **Chapter 4** describes the process of identifying and acquiring an appropriate grass court tennis dataset, and explains how these data were cleaned and their reliability assessed.

Applying the newly validated data analysis method, Chapters 5, 6 and 7 demonstrate a holistic approach to identifying important performance characteristics in men's and women's Wimbledon match-play. **Chapter 5** adopts a longitudinal perspective, **Chapter 6** investigates from the perspective of match closeness, and **Chapter 7** focuses on the time-constrained court surface transition from clay to grass between Roland Garros and Wimbledon. Informed by the findings, **Chapter 8** presents a more detailed investigation into the most important performance characteristic in grass court tennis – *points won of 0-4 shot rally length*. Subsequently, **Chapter 9** analyses Hawk-Eye (Hawk-Eye Innovations ltd, Basingstoke, UK) ball tracking data to examine the serving and returning strategies employed by men and women at Wimbledon. **Chapter 10** highlights how this thesis advances knowledge in the area of tennis notational analysis, and assimilates new knowledge to provide practical suggestions to ensure the representative learning design of players' grass court training sessions.

Chapter 2

Literature Review

2.1. Introduction to performance analysis in elite sport

Performance analysis is considered an integral component of sport science support for elite athletes (Glazier & Robins, 2013), progressing rapidly since its introduction in the 1970s. Sports performance analysis has typically incorporated two sub-disciplines; biomechanics and notational analysis (Hughes & Bartlett, 2002). Hand-notational analysis of sport was first documented when Downey (1973) published systems for analysing tennis and squash. Sanderson and Way (1977) then analysed the importance of tactics in squash using a notational system derived from Downey's (1973) work, before Hughes (1985) computerised Sanderson and Way's (1977) system to analyse tactical and technical contrasts between squash players of different playing standards. Now commonly a computerised process, notational analysis is an objective method of recording and analysing players' behaviours during sports competition and training (Gillet et al., 2009).

Hughes (1998) highlighted that sports notational analysis could facilitate several important processes: analysis of movement, technical and tactical evaluation, database development and the education of sports coaches and players. However, since then, the use of notational analysis as a sports science discipline has progressed, largely due to significant developments in the technology and methods used to record, store, analyse and report sports data (Lees, 2003). Computer software programmes such as SportsCode (Sportstec, Warriewood, Australia), NacSport (NacSport Elite, Las Palmas de Gran Canaria, Spain) and Dartfish (Dartfish, Friburg, Switzerland) have made notational analysis more accessible. Global Positioning Systems (GPS) such as Catapult (Catapult Innovations, Melbourne, Australia) have enabled time-motion analysis to be introduced as a third sub-discipline of sports performance analysis. In turn, these and other advancements, such as the introduction of smart-phone applications with performance analysis capabilities, have led to notational analysis becoming a sophisticated and accessible tool, with a more comprehensive range of applications for both individuals and teams within elite sport. As a result of these developments, notational analysis methods are now employed to identify strengths and areas for improvement (Sarmento et al., 2013), assess technical and tactical effectiveness (Passos et al., 2017), undertake opposition analysis (Groom et al., 2011), facilitate the development of athletes' training programmes (Reid et al., 2016), monitor injury rehabilitation (Blobel et al., 2017), identify successful patterns of play (Unierzyski & Wieczorek, 2004) and predict future performance outcomes (Kovalchik, 2016). Consequently, notational analysis of performance is considered of great applied importance to players and coaches in many sports (Groom et al., 2011).

2.2. Performance characteristics in notational analysis

Performance characteristics may be general (e.g. number of shots), biomechanical (e.g. ball projection velocity), technical (e.g. winners, errors) or tactical (e.g. shot distribution), and their analysis has significantly contributed to our understanding of the physiological, psychological, biomechanical and tactical demands of many sports (Hughes & Franks, 2015). Hughes and Bartlett (2002) highlighted the similarities between the performance characteristics used by analysts in different sports. Subsequently, they provided useful models of factors linked to success in each 'type' of sport; for example, 'factors that contribute to success or improved performance in net and wall games', such as tennis (see Figure 2.1.). Many performance characteristics collected today derive directly from Hughes and Bartlett's models.

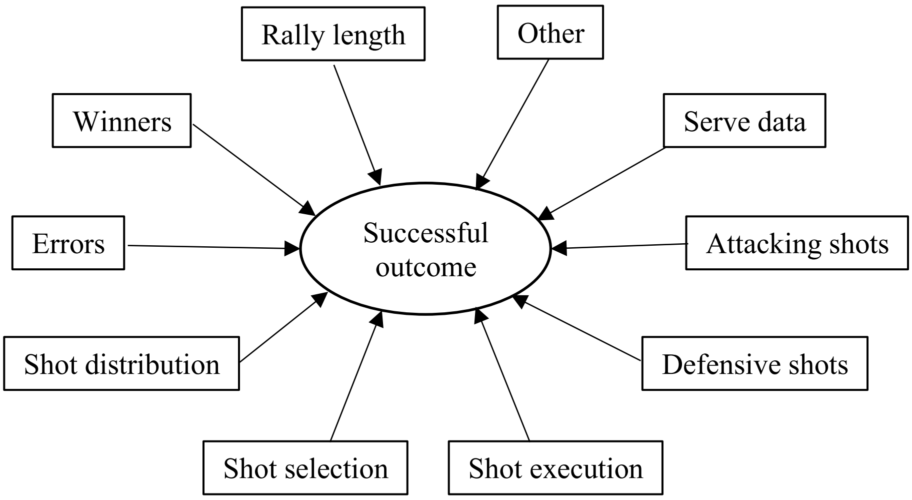


Figure 2.1. *Factors that contribute to success or improved performance in net and wall games (Hughes & Bartlett, 2002).*

Hughes and Bartlett (2002) highlighted that, if presented in isolation, a single set of data or a single performance characteristic can provide a distorted view of performance by ignoring other potentially important characteristics. Hughes and Bartlett (2002) added that the data provided by analysts are often insufficient, as they do not fully represent the important aspects of a particular performance. For example, Team A and Team B contest a football match; Team A lose possession of the ball 18 times during the match and Team B lose possession 12 times. These results may imply that Team B were the better performing side. However, if Team A had a total of 72 possessions and Team B had 36 possessions, then Team A lost possession in only 25% of cases, whereas Team B lost possession in 33% of cases, which suggests that Team A performed better. For this reason, non-dimensional variables (e.g. ratios), and/or normalised variables (e.g. percentages, occurrences per minute) are typically presented within notational analysis studies, as they offer a more accurate representation of performance.

2.3. Contemporary notational analysis research within tennis

Notational analysis is a valued discipline and well-established tool in sports such as soccer (Thompson, 2015), cycling (Trimble et al., 2010) and basketball (Scanlan et al., 2017), but the comparative progress of the discipline within tennis has been slow (Kovalchik & Reid, 2018). In 2012, a poll ranking 30 sports in terms of their use of performance data named tennis as the second least progressive, ahead only of boxing (Martin et al., 2012).

Since 2012, several notational analysis studies have been conducted within elite tennis, as part of a conscious effort to advance research in the area. Recently, for example, the physical demands and performance characteristics of professional tennis have been compared to those of the junior game (Kovalchik & Reid, 2017); it was reported that professional players hit their strokes (particularly the serve) harder and more accurately than juniors, and that professional male players moved almost twice as far as junior male players during matches. Sex-based differences in the stroke and movement characteristics of elite hard court tennis have also been examined (Reid et al., 2016), with results demonstrating that female players contacted the serve-return closer to the net and lower to the ground than male players, while distance covered did not differ by sex. Additionally, the prediction accuracy of different types of tennis match forecasting models has been assessed (Kovalchik, 2016). It was found that point-based, regression-based and paired-comparison models were 10-20% less accurate when predicting the outcome of matches involving lower ranked players, than matches involving higher ranked players. A comprehensive shot taxonomy has also been developed based on spatio-temporal match-play data (Kovalchik & Reid, 2018). Kovalchik and Reid (2018) analysed aspects including shot trajectory and shot velocity and identified 30 different types of forehand rally strokes for male players and 24 different types for female players; fewer types of serve and backhand rally strokes were identified for both sexes. Researchers have also begun to explore doubles match-play, with recent studies investigating point-ending characteristics (Martinez-Gallego et al., 2020) and serving and returning tactical formations in men's doubles (Kocib et al., 2020). Despite this conscious effort to advance tennis notational analysis research in recent years, several issues remain; these are explored later in this literature review.

2.4. Theoretical underpinning

2.4.1. Ecological dynamics

A key criticism of early notational analysis methods was the *descriptive* nature of the data typically collected and reported; although relevant performance information was provided, a theoretical lens that could explain decision-making and subsequent performance behaviours was lacking (Vilar et al., 2012). Derived from key aspects of ecological psychology, dynamical systems theory, non-linear thermodynamics and synergetics (Davids et al., 2013), ecological dynamics is a theoretical stance that considers sporting competition as a non-linear system based upon continuous spatio-temporal interrelations between performers (Glazier, 2010). From an ecological dynamics perspective, sports performers are complex, neurobiological systems, in which patterns emerge through the process of self-organisation, from the interaction of their many constraints (Warren, 2006). Constraints have been described as 'boundaries' that can restrict and/or facilitate the movement behaviours of an athlete during a sporting contest (Davids et al., 2008). Ecological dynamics proposes that an individual's decision-making and performance behaviours emerge from the interactions between that individual and the various constraints they are exposed to (Araújo et al., 2006); this process is explained in detail in Section 2.4.3.

2.4.2. Representative design

Brunswik's (1956) original concept of representative experimental design is a central notion within ecological dynamics. Often (erroneously) used interchangeably with 'ecological validity' (Araújo et al., 2007), representative experimental design pertains to the extent to which the conditions of an experiment represent the conditions toward which a generalisation is intended (Brunswik, 1956). For example, in a study examining the biomechanics of returning serve in tennis, to exhibit representative experimental design, a human should serve the balls to the returner, rather than an automated ball machine, as this would better reflect the conditions of the performance environment. Ecological validity on the other hand is the empirical relationship (correlation) between a visual cue and a distal criterion state in the environment (Brunswik, 1956). For example, the length of the grass on a tennis court is a cue that indicates the rate of acceleration of a bouncing tennis ball. This particular cue has high ecological validity because the rate of acceleration of the ball is highly correlated with the length of the grass. Brunswik believed that experimental cues (i.e. perceptual variables) should be sampled from an organism's environment in order to be representative of the environmental stimulation to which researchers wish to generalise their experimental data (Araújo et al., 2007). Furthermore, experimental designs should support the maintenance of coupled perception-action processes that reflect real-world, functional behaviours (Davids et al., 2012). In this context, decomposing a task into smaller, more manageable parts for the purpose of investigation must be carefully considered, as this may interfere with the important perception-action couplings of the movement (Davids et al., 2012).

As noted by Hammond and Stewart (2001), Brunswik used the word 'represent' in relation to representative design in the same way that one might describe a sample of participants within a study as 'representative' of individuals in some population not included in that study (e.g.

sampling participants according to their playing standard in a particular sport). In this sense, Brunswik was highlighting that logic of induction should be retained for environments, not just participants, if the generalisation of results is to be justified (Araújo et al., 2007).

In recent years, representative experimental design has been adopted within sports research, with the concept further developed by Pinder et al. (2011). Pinder et al. (2011) explained that, in addition to maintaining representative design within sporting experiments, sports *practice design* should also be representative of the performance context, if the development of functional movement patterns is to be effective. In this way, the constraints of training should replicate the performance environment where possible; this allows performers to detect affordances (opportunities for action, Fajen et al., 2008) and couple their actions to key information sources, while also ensuring they do not remain static (Davids et al., 2012). Static training drills have been criticised for lacking functionality, as they do not typically represent the constraints of performance and they restrict the exploratory processes of performers (Wilson et al., 2008). As a result, a more recent application of notational analysis in sport has been to facilitate the design of athletes' training sessions and practices, such that their training behaviours more closely reflect their match-play behaviours and functional movement patterns are more likely to emerge; this has become known as 'representative learning design' (Pinder et al., 2011). In this context, a more comprehensive understanding of sporting match-play behaviours better informs the representative learning design of elite athletes' training programmes.

2.4.3. Constraints-led approach

Newell's (1986) constraints-led approach, another key concept within ecological dynamics, seeks to identify how interacting constraints influence performance (Davids, 2010); it therefore provides an appropriate theoretical framework for many notational analysis studies. Newell's

(1986) constraints-led model (Figure 2.2.) demonstrates the mechanisms by which coordinated movement patterns emerge during goal directed behaviour (Davids, 2010). The model incorporates three categories of constraint: task (e.g. rules of the game, equipment); environment (e.g. court surface, air temperature); and performer (e.g. sex, age, anthropometry).

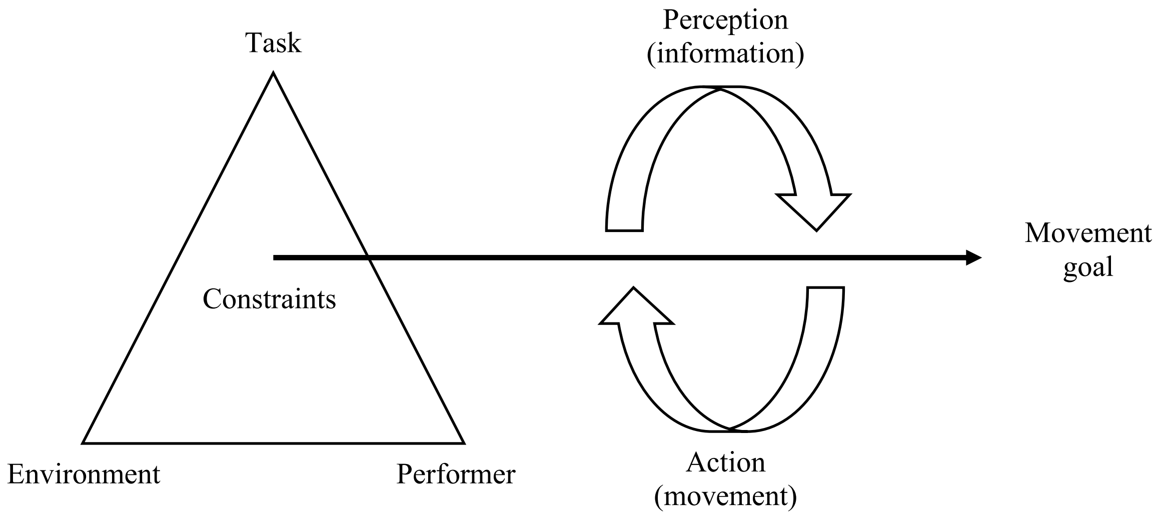


Figure 2.2. *Constraints-led approach model (adapted from Newell, 1986).*

The model illustrates that an athlete's perception of the interaction between task, environment and performer constraints determines their emergent behaviour (i.e. their action). The performer perceives this information and the resultant action is performed to achieve a specific goal (Renshaw et al., 2010). The model can be effectively explained using the sporting example of a serve-return in tennis. To successfully retrieve the ball, the returning player must assimilate information from the three types of constraint. The match might be contested on a particularly hot day, temperature being an environmental constraint; the returner may be left-handed, handedness being a performer constraint; and the server may be standing particularly close to the sideline, their position being a task constraint along with the incoming ball velocity and trajectory. The returning player's perception of this assimilated information informs what action (i.e. serve-return stroke) is most appropriate for them to execute in that specific scenario, to attempt to successfully return the ball into court.

The growing popularity of the constraints-led approach as a theoretical model has prompted researchers to investigate the influence of various constraints on sporting performance (Araújo et al., 2004). Such investigations are useful for assessing how the characteristics of a sport have changed over time, establishing how performance characteristics differ on different playing surfaces, for different playing positions and with different levels of match closeness, as well as investigating effects of rule changes. For example, Bush et al. (2015) showed that the number of passes and pass success rates in soccer have increased over time, but that the magnitudes of these increases depend on playing position; this type of information was then used to provide benchmarks for current elite players. Similarly, Murray et al. (2017) found that recent rule changes in elite squash (the new 11 point-per-rally scoring system and reduced tin height) decreased mean match duration and reduced the time players have to perform strokes. Murray et al. (2017) also found that more attacking strategies were adopted by squash players after these rule changes were implemented. Such studies are crucial; if notational analysis is to be employed to facilitate the development of athletes' training programmes, identify successful patterns of play and predict future performance behaviours, it is vital that the constraints of the performance environment are considered, to better inform these applications. For example, following Murray et al.'s (2017) squash study, which showed that the characteristics of match-play had changed after the new rules were introduced, implications for training and conditioning had to be assessed, to ensure players training behaviours closely resembled the recently changed characteristics of match-play.

2.4.4. Perturbations

In the context of ecological dynamics, the interaction between two players in a tennis match is considered a dyadic, dynamical system. Crucially, the constraints of performance in a tennis match change over time (Araújo & Davids, 2009). As such, within each point, the dyadic system is subject to great variability and therefore exhibits a continuously changing state of stability. When neither player has a tactical advantage during a rally, the system is said to be in a stable state or a state of dynamic equilibrium (Carvalho et al., 2013). For the point to end, this stable state must be disrupted by a 'perturbation', an instance that destabilises the system's dynamic equilibrium (McGarry et al., 2002). Three common approaches a sports performer can adopt to attempt to create (attacking) perturbations are: imposing their own style and tempo of play on the opponent; taking calculated risks; and making original or creative decisions during a contest (Lebed, 2017).

From a constraints perspective, within a dyadic sporting contest, the stability of the system can be destabilised when one performer manipulates the task constraints that their opponent must satisfy to achieve their goal; for example, by manipulating the amount of time and/or space their opponent has available to them to perform a stroke in tennis. In a practical sense, perturbations can occur as the result of either a particularly well-executed skill or a poorly executed skill (McGarry et al., 2002). For example, a perturbation in tennis might be caused by the returner performing a fast, well-executed serve-return that lands close to the baseline, at the server's feet. This would restrict the amount of time that the server has to move into an appropriate position to hit the next stroke (Filipcic et al., 2011), in turn decreasing the likelihood of them successfully retrieving the ball. Consequently, the returning player would hold a tactical advantage within the point. Alternatively, a poorly executed serve-return that travels high and slowly, landing close to the net would afford a tactical advantage to the server, as they would have plenty of time to prepare for their next stroke, as well as having an opportunity to strike the ball from a favourable position on the court and execute an attacking ball trajectory. Attacking perturbations typically lead to one of two outcomes; either a 'critical incident' occurs, such as a winning stroke being performed in tennis or a shot on goal attempted in football, or the perturbation is 'smoothed out' by effective defensive play (e.g. a block by a defender in football) or ineffective attacking play (e.g. a poor approach shot in tennis) (Hughes & Franks, 2008). Smoothing out a perturbation rebalances the dyadic system and re-establishes its dynamic equilibrium. In tennis, this is represented by the continuation of the point, whereby neither player holds a tactical advantage.

2.5. Important constraints in elite tennis

2.5.1. Court surface

Grand Slams are regarded as the most prestigious events of the annual tennis calendar (International Tennis Federation, 2019). The four Grand Slams are each contested on a different court surface and are spread throughout the calendar year. The Australian Open is played on hard courts (Plexicushion Prestige) in January, Roland Garros on clay courts in May/June, Wimbledon on grass courts in July and the US Open on hard courts (DecoTurf) in August/September (International Tennis Federation, 2019). As each court surface exhibits a different playing speed, it is considered an environmental constraint. The playing speed of any court surface can be thought of as sitting somewhere along a continuum, though hard and grass are typically thought of as 'fast' surfaces and clay as a 'slow' surface.

The speed of a court surface is largely determined by two elements: its coefficient of friction and its coefficient of restitution, both of which are constraints that affect the interaction between the tennis ball and the court surface each time the ball bounces (Brody, 1987). A court surface's coefficient of friction influences the horizontal component of a tennis ball's velocity, whereas its coefficient of restitution is related to the vertical component of a ball's velocity (White, 2011). On a court surface with a low coefficient of friction, the ball loses less horizontal velocity than on a surface with a high coefficient of friction, and on a court surface with a low coefficient of restitution, the ball bounces lower than on a surface with a high coefficient of restitution.

Court surface has consistently been shown to influence the characteristics of tennis match-play (i.e. the way the game is played) (Reid et al., 2016; Sogut, 2019). Several studies have demonstrated that mean rally length (number of shots per rally) and rally duration (i.e. time) are shortest on Wimbledon's grass courts and longest on the clay courts of Roland Garros (Unierzyski & Wieczorek, 2004; Brown & O'Donoghue, 2008), with rally length and duration at the Australian Open and US Open (i.e. on hard courts) typically somewhere in between (O'Donoghue & Ingram, 2001). These results appear to correspond to the previously mentioned notion that clay courts are slower than hard and grass courts. The slower, relatively gentle bounce on a clay court affords players more time to retrieve each stroke (O'Donoghue & Ingram, 2001). So, when the ball bounces, the velocity of a fast, well-executed stroke (that might typically be difficult to retrieve) is reduced more on a clay court than on other court surfaces, thus, decreasing the likelihood of the well-executed shot causing a perturbation, and in turn resulting in longer rallies.

In terms of representative *learning* design, it is now well documented that our understanding of tennis match-play characteristics should be used to help guide and structure the development of on- and off-court training programmes (Kovacs, 2006). For example, it is advised that most training practices in tennis should simulate the time requirements of match-play, in terms of total duration and work-to-rest ratios (Kovacs, 2006; Reid et al., 2016). The information from studies investigating tennis match-play on different court surfaces can therefore better inform players' training and match-play strategies, which should be specific to the court surface they will next compete on (O'Donoghue & Ingram, 2001). Such investigations enable the periodisation and representative design of training according to court surface, whereby a player's tournament schedule is split into sub-seasons (e.g. the grass court season, the clay court season), which are characterised by surface-specific training methods. For example, if net-play is most prominent on grass courts, this should be reflected during training sessions, with approach shots and net-play afforded more practice time during the grass court sub-season than other sub-seasons.

In recent years, most studies relating to performance analysis in elite tennis have focused on hard court match-play (e.g. Reid et al., 2016; Kovalchik & Reid, 2017; Martinez-Gallego et al., 2019; Martinez-Gallego et al., 2020) or clay court match-play (e.g. Fernandez-Fernandez et al., 2009; Costa Pereira et al., 2017). For example, Costa Pereira et al. (2017) found that on clay courts, female players move approximately 3.2 km during a match, covering less distance in the second set of matches compared with the first set. In contrast, Reid et al. (2016) reported that on hard courts, female players cover only 1.2 km during a match, highlighting some disparity between match-play contested on the two different surfaces. Costa Pereira et al. (2017) added that forehand groundstroke technical proficiency (i.e. percentage of successful forehand strokes) decreased in the second set of matches on clay compared with the first set, which indicated a possible fatigue effect. As a result of these studies, some recommendations are available for players preparing for events on hard and clay court surfaces. However, such recommendations are not available for grass courts, despite the world's most prestigious tournament – Wimbledon (Gourville & Arnold, 2017) – taking place on the surface.

A recent study investigated grass court match-play at the 2012 Olympic Games (Fernandez-Garcia et al., 2019). Winning players of both sexes won a higher percentage of second serve points, break points and net points, and performed more forehand and backhand winners than losing players (Fernandez-Garcia et al., 2019). While results from this study may provide a reference point for future work, the tennis event at the Olympic Games differs from Grand Slams in a number of ways. Firstly, the qualification and eligibility criteria for the Olympic Games are unique: stipulations exist around players' previous involvement in the Davis Cup and Fed Cup competitions; the number of players from any single nation permitted to compete is restricted; and several places are reserved for (potentially much lower-ranked) players from nations who have no directly accepted competitors (International Tennis Federation, 2020a). Secondly, in contrast to many other sports, the Olympic Games does not represent the pinnacle of an athlete's career for tennis players (Harris, 2019). As a result, some players elect not to compete, and those that do compete are more likely to target 'peak' performance levels for the Grand Slams that occur shortly before (Wimbledon) and after (US Open) the Olympics, rather than the Olympics itself, potentially further weakening the standard of competition. Fernandez-Garcia et al. (2019) also noted that their results were only applicable to best of three set matches (Grand Slams are contested over five sets for male players) and highlighted the need for further research to identify performance characteristics associated with success, particularly in the women's game. Consequently, results from analysis of tennis match-play at the Olympic Games should not be generalised to players competing in Grand Slams.

A small number of other studies have analysed specific elements of grass court match-play. O'Donoghue and Liddle (1998a) compared time characteristics of elite men's and women's grass and clay court match-play. Women's rally durations were longer than men's on both surfaces, and grass courts elicited shorter rally durations than clay courts, irrespective of sex; a finding that has remained consistent over time (O'Donoghue & Ingram, 2001; Brown & O'Donoghue, 2008; Lane et al., 2017). Women also spent a greater percentage of total match time playing points (as opposed to in between points) than men on both surfaces (O'Donoghue & Liddle, 1998a). O'Donoghue and Liddle (1998b) analysed differences between elite women's point outcomes on grass and clay courts, discovering that grass courts elicited more serve winners and more net-play than clay courts. Hughes and Moore (1998) analysed the footwork associated with men's serve-volley strategy on grass. It was revealed that the large majority of strokes performed were preceded by a split-step and an appropriate ready position, and that errors were more common when a player failed to perform either one or both of these preparatory actions. Brown and O'Donoghue (2008) and Cross (2014) have published brief overviews of the differences between Grand Slam match-play on grass, clay and hard court surfaces. Both articles found that, irrespective of sex, aces were most common on grass courts, with Cross (2014) adding that breaks of serve were least common on grass courts. These results indicate that the serve may be more important on grass than other surfaces; a notion commonly asserted by practitioners and within the literature (e.g. Anderson, 2009; Gillet et al., 2009), but rarely researched empirically.

While these aforementioned studies analysed grass court match-play, the data collection and analysis technology available at the time greatly restricted their sample sizes [e.g. n ≈ 10 matches per group in O'Donoghue & Liddle (1998a; 1998b), n = 7 matches in Hughes & Moore (1998)], which limits the application of any results. So, in comparison to clay and hard court tennis, grass court tennis has been underrepresented within published research. In this respect, within their study of hard court match-play, Reid et al. (2016) recommended future detailed investigations of match-play on other court surfaces, such as grass. While addressing this issue would undoubtedly benefit players of all nationalities, such research may be particularly pertinent for British players, as typically, the grass court season (especially Wimbledon) presents a valuable opportunity for them to raise their public profiles.

2.5.2. Sex of a player

In elite tennis singles events, male and female players compete separately. The sex of a player, a performer constraint, has been shown to influence match-play (Reid et al., 2016).

O’Donoghue and Ingram (2001) reported that women’s rally durations were longer than men’s rally durations at all four Grand Slams, a finding that both supported and furthered the work of O’Donoghue and Liddle (1998a), who compared men’s and women’s match-play only at Roland Garros and Wimbledon. This may be linked to the tendency for male players to approach the net more often than female players (O’Donoghue & Ingram, 2001); if a player approaches the net, the ball will travel a shorter distance between strokes, thus affording players less time to perform each stroke and potentially increasing the chance of a perturbation occurring, which could end the rally sooner than if both players had remained at the baseline. In contrast to previous findings, Brown and O’Donoghue (2008) found that men’s rally durations at the Australian Open and Roland Garros in 2007 were longer than women’s. The authors speculated that the disparity between their results and those of O’Donoghue and Ingram (2001) may be due to the improved fitness and technical ability of male players since O’Donoghue and Ingram’s data collection, a decade earlier.

Women have also been shown to perform a greater proportion of baseline rallies than men on all court surfaces, and grass courts have elicited the lowest proportion of baseline points (compared to net-play points), irrespective of sex (O’Donoghue & Ingram, 2001). Men have consistently served faster than women, achieving a lower successful first serve percentage but winning a higher percentage of points when their first serve lands in the court (O’Donoghue & Ballantyne, 2003; Gillet et al., 2009; Reid et al., 2016).

Studies investigating sex differences are crucial for the sport as they facilitate a deeper understanding of the way the game is played by male and female players. In turn, this provides a platform for coaches to plan appropriate practice sessions and tactical game plans for their players with increased specificity. A comprehensive investigation of male and female grass court tennis at Grand Slam level has not been published within the last 20 years, the most recent being a comparison of all four Grand Slams by O'Donoghue and Ingram (2001), which is discussed below. It is crucial to address this to support coaches in their planning and preparation of key elements of players' grass court training and match-play.

2.5.3. Time

It is well-documented that the characteristics of elite sports performance change over time (Foster, 2012). For this reason, notational analysis findings are only applicable to the era in which they were observed (O'Donoghue, 2004). In this respect, Kovacs (2006) asserted that although quality tennis notational analysis research was conducted in the 1980s and 1990s, insufficient match-play data had been analysed since then. Probably the most comprehensive study of elite tennis match-play was carried out by O'Donoghue and Ingram (2001), in the form of a theoretical match investigation, whereby data from multiple matches are used to identify the typical performance characteristics of a sport (O'Donoghue, 2004). Sections of 252 matches were coded in order to compare men's and women's match-play at each of the Grand Slam events contested between May 1997 and January 1999. Sex differences and court surface differences were discussed, although little indication of how the information could be used to enhance players' training or competitive performance was provided. Crucially, this research analysed data collected over 20 years ago. Since then, the speed of the game has changed (Kovacs, 2006), racket and ball technologies have progressed (Brown & O'Donoghue, 2008), a line-call challenge system has been introduced (Kovalchik et al., 2017), court surface properties have been manipulated (Miller, 2006) and players' mental, tactical, technical and physical abilities have changed (Takahashi et al., 2009). All of these factors are constraints that may have influenced the characteristics of elite tennis performance over time. For this reason, it is important to establish up-to-date accounts of elite men's and women's match-play.

While cross-sectional research is relatively common in tennis, one of the most notable shortfalls within the literature is the lack of longitudinal studies and time-series analyses. Such studies are important for a number of reasons; firstly, analysing the same variables over several years can reveal temporal patterns including linear trends and cyclical components within the data (Fok & Ramsay, 2006). Secondly, they allow us to quantify the influence of factors such as rule changes and new technologies on performance. For example, Foster (2012) plotted temporal performance improvements in women's 100m sprint times and was subsequently able to quantify the negative influence of enhanced drug testing procedures being introduced (in 1989) on sprint performance. Such studies highlight the importance of researching potential rule changes or new technologies within a sport prior to their introduction, as well as facilitating a better understanding of how such factors might influence performance. Longitudinal studies and time-series analyses also allow us to consider whether the level of variability in performance has changed over time, and enable predictions of how a sport is likely to progress in coming years, which can contribute to aspects such as talent identification (Kramer et al., 2017).

A longitudinal study of elite tennis match-play was presented by Takahashi et al. (2009), who analysed time characteristics of elite men's match-play at Wimbledon over three decades. Rally durations and rally lengths were found to be longer in the 2000s than in the 1980s and 1990s, whereas the time duration between players' strokes was shorter in the 2000s than in the two previous decades. While these findings may be of interest, the data could not claim to be truly representative of elite tennis of the era; the sample size was limited to two Wimbledon finals per decade (i.e. a total of six matches). With this in mind, it cannot be assumed that Takahashi et al.'s (2009) results would have been replicated in all elite match-play during the decades investigated. As mentioned previously, small sample size was a common issue for early notational analysis studies, as the technology required for large-scale data collection was not developed until more recently.

Brown and O'Donoghue (2008) analysed elite men's and women's Grand Slam match-play in 2007, replicating O'Donoghue and Ingram's (2001) investigation of sex and court surface effects on Grand Slam match-play in the late 1990s. Brown and O'Donoghue (2008) compared some of their results to those of O'Donoghue and Ingram (2001), noting that while men's rally durations increased at all four Grand Slams between 1999 and 2007, women's rally durations decreased at all Grand Slams, except Wimbledon, in the same period of time. The dominance of men's serves also appeared to decrease between 1999 and 2007, whereas women won more points using their serve in 2007 than in 1999. Despite observing temporal 'differences', Brown and O'Donoghue's (2008) work did not comprise a longitudinal study; it simply provided a comparison to previous work.

Cross (2014) presented longitudinal data from match-play at the four Grand Slams between 2000 and 2013. However, the discussion centred around overall differences between male and female players, rather than temporal aspects, which were not considered. Additionally, the article lacked detail, few performance characteristics were included and those presented were basic (e.g. percentage of serve games won, number of sets per tiebreak), and summary data were used, so no statistical analysis was carried out. Without doubt, to further progress research in this area, comprehensive longitudinal analyses are crucial, to better understand how tennis has changed over time and facilitate predictions of how the sport is likely to progress in the coming years.

2.6. Important performance characteristics in elite tennis

Tennis notational analysis studies investigating sex, court surface and longitudinal factors are crucial to inform wide ranging applications, such as developing normative performance profiles (e.g. O'Donoghue, 2005; Takahashi et al., 2009), identifying performance characteristics closely associated with success (e.g. Csataljay et al., 2009), and establishing effects of specific interventions or independent variables on performance behaviours (e.g. Di Salvo et al., 2007; Fitzpatrick et al., 2018). Importantly, before such research can be undertaken, an evaluation of which performance characteristics should be examined is required. With regards to this, O'Donoghue (2002) highlighted a key shortfall of notational analysis research in elite tennis. Although the performance characteristics of match-play (i.e. normative profiles of tennis) had been established, no study had sought to identify the performance characteristics that differentiate winning and losing players (i.e. performance characteristics associated with success). Such studies can provide crucial information for coaches and players regarding the most important match-play aspects to focus on during training (Reid et al., 2010), and while general profiles of a sport are useful, identifying what constitutes winning is more practically relevant to those involved at elite level.

O'Donoghue (2002) subsequently made some progress in this area by identifying the performance characteristics most closely associated with success in elite men's and women's hard court tennis. Reid et al. (2010) also contributed to this line of research, analysing data from matches involving Association of Tennis Professionals (ATP) top 100 players during 2007, to establish the performance characteristics that were most closely associated to men's world ranking. Although Reid et al.'s (2010) study revealed useful information, court surface differences were not considered, therefore the work did not facilitate surface-specific applications. To address this, Sogut (2019) recently investigated surface-related variations in match-play outcomes and men's (ATP) world rankings. However, these three studies designed to identify performance characteristics associated with success (i.e. O'Donoghue, 2002, Reid et al., 2010 and Sogut, 2019) demonstrated somewhat inconsistent results. O'Donoghue (2002) found that the number of break points converted best distinguished winning players from losing players of both sexes, whereas Reid et al. (2010) found that the percentage of second serve points won and the percentage of second serve-return points won were the best predictors of men's world ranking. Sogut (2019) reported that predominantly serve-related characteristics, including the percentage of first serve points won, the number of serve games won and the number of serve points won were associated with men's world ranking on grass, clay and hard court surfaces. This disparity between results may be due to differences over time, methodological differences, such as the performance characteristics selected for inclusion and their operational definitions, the data analysis methods employed, and as noted by Sogut (2019), the inclusion of data from several court surfaces combined (e.g. Reid et al., 2010), as opposed to data stratified by court surface (e.g. Sogut, 2019), or data from a single court surface (e.g. O'Donoghue, 2002).

Recently, Fernandez-Garcia et al. (2019) investigated winner-loser differences in men's and women's tennis match-play at the 2012 Olympic Games, contested on grass courts. Results demonstrated that the percentage of break points won best discriminated winning and losing players of both sexes. This concurs with O'Donoghue's (2002) findings, but further work would be required to understand how break point opportunities are created and how break points are won. Additionally, tennis at the Olympic Games should not be considered comparable to Grand Slam tennis, for the reasons highlighted in Section 2.5.1.

Several tennis practitioners, with vast experience and knowledge of the sport, believe the serve and serve-return to be vitally important strokes in tennis (e.g. Ruder, 2019; O'Shannessy, 2019a). Some studies have subjectively described the serve and serve-return as the most important strokes, as all points in tennis begin with a serve, potentially followed by a serve-return (e.g. Gillet et al., 2009; Klaus et al., 2017). Although these strokes may be important, the studies making this assertion have focused solely on the serve and serve-return, rather than all aspects of match-play, so they have not objectively established their superior importance in comparison to other strokes. Several tennis practitioners have also professed the importance of the first four strokes of each point during match-play, including the serve and serve-return (Annacone, 2018; Pretorius & Boucek, 2019; O'Shannessy, 2019a), but the significance of different strokes and rally lengths has not yet been explored empirically. Other attempts to identify performance characteristics associated with success in tennis have considered players' fitness characteristics, such as medicine ball throwing distance and 5 m sprint time (e.g. Ulbricht et al., 2016, Kramer et al., 2017), rather than match-play characteristics. Therefore, it remains unclear which match-play characteristics are the most important in terms of winning elite tennis matches for male and female players.

2.7. Barriers to the application of notational analysis within tennis

2.7.1. The cost of employing an analyst

Notational analysis can provide important insights into tennis performance, and inform current practice, however, as highlighted, the discipline has not progressed in tennis the way it has in many other sports. The associated cost is a contributing factor (Briggs, 2018). In team sports, one analyst can be employed to work with over 20 players, whereas an analyst's salary is more difficult to justify for athletes competing in individual sports, such as tennis. So, even at tennis' elite level, it is uncommon for players to employ an analyst or attempt to exploit the vast amounts of data available to them (Fernandez-Garcia et al., 2019). Instead, coaches (before and after matches) and players (during matches) typically attempt to fulfil the role of analyst themselves (Over & O'Donoghue, 2008; Briggs, 2018), but this match-by-match approach lacks objectivity and risks neglecting long-term performance development in favour of identifying short-term solutions. Additionally, although players may know their tournament schedule months in advance, their next opponent is often revealed less than 24 hours before a match (Briggs, 2018); the amount of opposition analysis that can be undertaken within that time is limited.

2.7.2. Tennis coaches' resistance

Some coaches and organisations within the sport have also hindered the progress of notational analysis, showing resistance to technological advancements (Kovalchik & Reid, 2018). Tennis coaches tend to be former players, who competed at a time when large-scale, systematic data collection was not possible; therefore, they may be more comfortable trusting their own subjective judgements than notational analysis data (Briggs, 2018). To compound this issue, some analysts have little or no experience of elite tennis, so coaches and players, who have often dedicated decades of their lives to the sport, may find it difficult to take advice from less experienced analysts. It is clear that these issues must be ameliorated if the discipline is to be fully incorporated and utilised optimally within the sport.

2.7.3. Complex datasets and methods

With the development of increasingly sophisticated methods for monitoring and recording aspects of tennis match-play, data collection has become easier and more prevalent (Mecheri et al., 2016). Consequently, huge amounts of data are now readily and freely available to players. Typically, however, time-consuming data processing and complex analysis techniques are required to uncover useful information (Briggs, 2018), particularly when the data were recorded using motion tracking systems such as Hawk-Eye (Hawk-Eye Innovations ltd, Basingstoke, UK). For example, a recent study analysing Hawk-Eye data featured several stages of data cleaning and processing before analysis could be undertaken to examine the relationship between serve ball trajectory and point-winning probabilities (Mecheri et al., 2016). Even analysing and interpreting relatively simple notational analysis data requires time and a degree of statistical knowledge. Previous studies seeking to identify important performance characteristics in various sports have employed Pearson's correlation coefficients, log transformations and stepwise regression procedures (tennis; Reid et al., 2010), Student's *t*-tests (tennis; O'Donoghue, 2002, basketball; Scanlan et al., 2017), discriminant analysis (rugby union; Ortega et al., 2009) and Kruskal-Wallis H (soccer; Lago-Penas et al., 2010). Taking this into account, coaches are not likely to have the time (Reilly et al., 2009), nor the desire (Briggs, 2018) to analyse these large quantities of data, nor potentially the expertise to transform the datasets into meaningful interpretations with respect to tennis (Over & O'Donoghue, 2008; Hughes & Franks, 2015). A simpler analysis method that is easy to calculate, understand and contextualise, may benefit coaches by making notational analysis more accessible and user-friendly, as well as less intimidating.

It is worth noting here, that although the Briggs (2018) citation derives from a newspaper article, the interviewee was Dr Machar Reid, a well-respected, world-renowned tennis data analyst (currently Head of Innovation at Tennis Australia).

2.7.4. Less-representative studies

In addition to the previously mentioned lack of comprehensive longitudinal analyses and often low sample sizes, several studies analysing aspects of elite tennis performance have suffered from less-representative participant samples (e.g. sub-elite; Costa Pereira et al., 2017) and less-representative study designs (e.g. training or simulated match-play; Martin et al., 2011). These issues have limited the practical relevance and generalisability of results (Reid et al., 2016).

2.8. Summary

Notational analysis is a valued discipline and well-established tool in many sports, with a wide range of practical applications. Despite this, notational analysis has not progressed in tennis the way it has in other sports. Grass court tennis has been underrepresented within the research, particularly considering that the world's most prestigious tournament is contested on the surface; and in turn, no grass court training recommendations are available for elite players and coaches based on empirical research. Studies have often exhibited small sample sizes and/or less-representative study designs. The most prominent investigation of elite tennis performance is outdated, having analysed match-play from over 20 years ago, and no comprehensive longitudinal analyses have been undertaken. Few attempts have been made to identify performance characteristics associated with success, and those that have demonstrated inconsistent results. Operational definitions have been absent or inconsistent across previous publications, and finally, although a wealth of performance data is freely available, tennis coaches and organisations have not embraced notational analysis to the extent of those in other sports, partly due to the time-consuming data processing techniques and complex analysis methods typically required. Some of these issues have limited the practical relevance and generalisability of previous research, and others have contributed to the lack of progress of notational analysis in tennis compared with other sports. Furthermore, this inadequate progress has considerably restricted the extent to which coaches can fully implement the concept of representative design within their training sessions (Pinder et al., 2011). The aim and objectives of the work presented in this thesis, displayed below, were designed to address these issues.

2.9. Thesis aim and objectives

Aim: To provide practical recommendations to enhance the representative design of grass court training within elite tennis.

Objective 1: To develop and validate an appropriate, practitioner-friendly data analysis method for identifying performance characteristics associated with success in elite tennis.

Objective 2: To acquire, clean and assess the reliability of elite grass court tennis match-play data.

Objective 3: To identify important performance characteristics in elite grass court tennis.

Objective 4: To investigate the most important performance characteristic in greater depth using tennis ball-tracking data.

Objective 5: To provide recommendations that facilitate the representative design of tennis players' grass court training, to increase their likelihood of success at Wimbledon.

Chapter 3

A simple new method for identifying important performance characteristics in elite tennis

This chapter introduces a new method for identifying performance characteristics associated with success in elite tennis, which is simpler, easier to calculate and more intuitive than many standard data analysis methods. The new method is compared to two previously used methods to assess its validity.

This chapter is based on the following peer-reviewed journal article: Fitzpatrick, A., Stone, J. A., Choppin, S. and Kelley, J. (2019a). A simple new method for identifying performance characteristics associated with success in elite tennis. *International Journal of Sports Science and Coaching, 14*(1), 43-50.

3.1. Introduction

As discussed in the Literature Review (Chapter 2), the progress of performance analysis in tennis has been slow (Kovalchik & Reid, 2018) particularly compared with sports such as cycling and football in which the discipline has been widely embraced and performance data facilitates everyday working practices. To advance performance analysis research in tennis, theoretical match investigations, in which multiple matches are analysed to identify the typical performance characteristics of a sport (O'Donoghue, 2004), could be employed. Theoretical match investigations are helpful for identifying performance characteristics associated with success, monitoring the characteristics of a sport over time, on different playing surfaces and for varying playing positions, as well as investigating the influence of rule changes. For example, a theoretical match investigation in elite squash showed that recent changes to the tin height and scoring system reduced both the average duration of matches and the amount of time competitors have to perform strokes (Murray et al., 2017). The implementation of these rule changes also influenced competitors' playing strategies, with many adopting a more attacking style of play. Changes to playing styles meant that elite squash players' training regimes had to be adapted, to ensure that their training behaviours closely represented their match-play behaviours.

With the development of increasingly sophisticated methods for monitoring and recording aspects of tennis match-play performance, data collection has become more prevalent (Mecheri et al., 2016), and large quantities of data are available to players. Despite this, translating these data into meaningful, practitioner-friendly insights can require time and complex techniques (Briggs, 2018). For example, to glean useful information from Hawk-Eye tracking data, many iterations of data cleaning and further processing must be executed (Mecheri et al., 2016), before data analysis methods can be considered. Even translating relatively simple sports data, such as notational analysis, into useful information requires time and statistical knowledge. The often complex data analysis methods mean that coaches do not typically have the time, the desire (Briggs, 2018) or potentially the knowledge to translate the data into meaningful interpretations to apply within their work (Hughes & Franks, 2015).

The majority of tennis players cannot (financially) afford to employ an analyst to objectively oversee their long-term development. Additionally, tennis coaches are often reluctant to accept information and advice from analysts with comparatively less experience of elite tennis (Briggs, 2018). Coaches' resistance to embrace performance analysis and its complex and often intimidating data analysis methods, has contributed to the limited progress of the discipline within tennis. Furthermore, first-hand experience of professional tennis has highlighted a communication disconnect between performance analysts on one side, and players and coaches on the other. The literature supports this observation, with 'gaps' between research and coaching practice often referred to by sports practitioners (Goldsmith, 2000). A data analysis method that is easy to understand and contextualise may help make performance analysis less intimidating, more accessible and more user-friendly for players and coaches. Therefore, the researcher developed a simple percentage-based method for identifying performance characteristics associated with success.

The aim of this study was to establish the validity of the simple new method for identifying performance characteristics associated with success in tennis, by testing the agreement between the results of the simple method and results of two standard statistical methods. The standard methods are: 1) paired *t*-tests, as used by O'Donoghue (2002) and Scanlan et al. (2017) to identify match-play characteristics associated with success in tennis and basketball, respectively; and 2) point-biserial correlations, used by Cowden (2016) to investigate the association between mental toughness and match outcome in tennis, and Scanlan et al. (2017) to assess the association between basketball game characteristics and match outcome. Analysis was undertaken using sample data from men's and women's elite tennis match-play at Roland Garros, contested on clay courts.

3.2. Method

3.2.1. Matches

With institutional ethics approval, performance characteristics for the 2016 and 2017 Roland Garros men's (n = 244) and women's (n = 250) singles matches were obtained from the Roland Garros (2017) website. All performance characteristics available on the website were included. Incomplete matches (i.e. walkovers, retirements and defaults) were excluded from the study.

3.2.2. Performance characteristics

The following performance characteristics were collected for both players in each match (for a full list of definitions, see Appendix A):

- number of aces, number of double faults
- number of first serves in
- average (i.e. mean) first serve speed*
- number of first serve points won, number of second serve points won
- number of first serve-return points won, number of second serve-return points won
- number of baseline points won, number of net points won
- number of break points won
- number of winners, number of forced errors, number of unforced errors
- number of points won of 0-4, 5-8 and 9+ shot rally length+, respectively*.

* Collected only for those matches where a serve speed radar was available.

+ The rally length of a point is comprised only of successful strokes (i.e. strokes whereby the ball crosses the net, to the side of the opponent, and lands inside the court); errors are not counted.

These performance characteristics were selected for analysis for several reasons: they are closely aligned to Hughes and Bartlett's (2002) 'factors that contribute to success' in net and wall sports; they are considered meaningful by tennis coaches and players; and they are commonly used by media outlets to summarise tennis matches.

The data were stratified by sex and match outcome (i.e. winning player or losing player) and normalised using the calculations in Table 3.1., before being reduced to mean values (± *sd*).

Table 3.1. *Normalised performance characteristic calculations for Roland Garros, derived from O'Donoghue and Ingram (2001) and O'Donoghue (2005).*

Performance characteristic	Calculation
Aces (%)	Number of aces/number of serves performed x 100
Double faults (%)	Number of double faults/number of points served x 100
Successful first serves (%)	Number of first serves in/number of first serves attempted x 100
First serve points won (%)	Number of first serve points won/number of first serve points played x 100
First serve-return points won (%)	Number of first serve-return points won/number of first serve-return points played x 100
Second serve points won (%)	Number of second serve points won/number of second serve points played x 100
Second serve-return points won (%)	Number of second serve-return points won/number of second serve-return points played x 100
Break points won (%)	Number of break points won as returner/number of break points played as returner x 100
Net points won (%)	Number of net points won/number of net points played x 100
Baseline points won (%)	Number of baseline points won/number of baseline points played x 100
Winners (%)	Number of winners/number of rally points played x 100
Forced errors (%)	Number of forced errors/number of rally points played x 100
Unforced errors (%)	Number of unforced errors/number of rally points played x 100
Points won of 0-4 shot rally length (%)	Number of points won of 0-4 rally length/number of points played of 0-4 rally length x 100
Points won of 5-8 shot rally length (%)	Number of points won of 5-8 rally length/number of points played of 5-8 rally length x 100
Points won of 9+ shot rally length (%)	Number of points won of 9+ rally length/number of points played of 9+ rally length x 100

Note: the denominator differs between calculations, depending on the numerator and associated performance characteristic.

3.2.3. Data analysis

Statistical correlation-based method: Normalised data were imported into in SPSS (v23.0, SPSS Inc, USA). Point-biserial correlations can be used to measure the strength of association between two variables when one variable is continuous and the other is dichotomous (Field, 2013). Point-biserial correlations between match outcome and each performance characteristic were calculated, to identify which characteristics were associated with match outcome, for both sexes.

Statistical paired t-test method: For each performance characteristic, a paired *t*-test was used to compare winning and losing players' data, for each sex, with the simplifying assumption of normality of the winner-loser differences. The *t* values were used to identify the performance characteristics that best distinguished between winning and losing players (O'Donoghue, 2002).

Proposed method: For each performance characteristic, the winning player's performance was compared to that of their opponent (i.e. the losing player) at match level, to identify which player 'outscored' the other. Then, the *Percentage of matches in which the Winner Outscored the Loser* (PWOL) was calculated for each performance characteristic. For example, if the winning player hit *more* aces than (i.e. outscored) the losing player in 80 out of 100 matches, the PWOL for aces would be 80%. Similarly, if the winning player hit *more* unforced errors than (i.e. outscored) the losing player in 40 out of 100 matches, the PWOL for unforced errors would be 40%; this would mean that the losing player hit *more* unforced errors than the winning player in 60% of matches. To the researcher's knowledge, the method has not previously been applied within sports performance analysis. Table 3.2. displays sample (fictitious) match-play data, stratified by match outcome (i.e. winning and losing player) and demonstrates the process for calculating PWOL.

Table 3.2. *Sample match-play data for a single performance characteristic (aces %) and associated PWOL calculation.*

Match ID	Winning player			Losing player			PWOL
	Number of aces	Total number of serves attempted	Aces (%)	Number of aces	Total number of serves attempted	Aces (%)	1 or 0
1	5	119	4.2%	3	151	2.0%	1
2	21	110	19.1%	5	167	3.0%	1
3	26	200	13.0%	19	242	7.9%	1
4	9	198	4.5%	6	226	2.7%	1
5	17	133	12.8%	5	137	3.6%	1
6	8	174	4.6%	11	187	5.9%	0
7	9	123	7.3%	8	158	5.1%	1
8	7	96	7.3%	7	113	6.2%	1
9	11	190	5.8%	36	203	17.7%	0
10	28	77	36.4%	0	128	0.0%	1

If winning player *aces* (%) > losing player *aces* (%) at match level, this cell = 1, otherwise = 0. e.g. Match ID 1: 4.2% > 2.0%, PWOL cell = 1, Match ID 6: 4.6% < 5.9%, PWOL cell = 0.

$$\text{PWOL (\%)} = \frac{\text{Count (1)}}{\text{Count (total)}} \times 100$$

$$\text{PWOL (\%)} = \frac{8}{10} \times 100 = \mathbf{80\%}$$

A PWOL value of 50% for a particular performance characteristic means that players who outscored their opponent won the match in 50% of cases, indicating no association with match outcome. As the PWOL value increases towards 100%, this indicates a stronger positive association with match outcome or success. Correspondingly, as the PWOL value decreases towards 0%, this indicates a stronger negative association with match outcome (i.e. a stronger association with losing). Therefore, performance characteristics with either a high PWOL value or a low PWOL value are considered important, whereas those with PWOL values close to 50% are considered less important. PWOL values are simple to calculate, with no need for statistical software packages, such as SPSS. Furthermore, users do not require a comprehensive understanding of data analysis techniques to apply the method or interpret the results, so it may be more suitable for coaches and other practitioners.

The results of each of the three methods were used to indicate the relative importance of each performance characteristic. To assess the agreement between the results of the methods, and establish the validity of the PWOL method, pairwise comparisons between the PWOL values, *t* values and point-biserial correlation coefficients were performed using Spearman's rank-order correlations.

3.3. Results

Table 3.3. (men) and Table 3.4. (women) show the mean and standard deviation of the performance characteristics for winning and losing players. Tables 3.3. and 3.4. also show the results of each statistical method; point-biserial correlations between each performance characteristic and match outcome (r_{pb}), *t* values from paired *t*-tests comparing winning and losing players (*t*) and the Percentage of matches in which the Winner Outscored the Loser (PWOL).

Table 3.3. *Men's performance characteristics (presented as mean ± sd), point-biserial correlations with match outcome, t values and PWOL values (± 95% confidence intervals); sorted by r_{pb}.*

Performance characteristic	Winning players	Losing players	r_{pb}	t_{dof}[*]	PWOL
Points won of 0-4 shot rally length (%)	55.2 ± 5.0%	44.8 ± 5.0%	0.72	44.47_{180}	89.0 (± 4.6%)
Baseline points won (%)	53.1 ± 6.5%	42.2 ± 6.3%	0.65	48.43_{243}	82.4 (± 4.8%)
First serve points won (%)	74.7 ± 8.1%	65.1 ± 8.3%	0.51	45.64_{243}	85.2 (± 4.5%)
First serve-return points won (%)[+]	34.9 ± 8.3%	25.3 ± 8.1%	0.51	45.64_{243}	85.2 (± 4.5%)
Points won of 5-8 shot rally length (%)	54.4 ± 8.1%	45.6 ± 8.1%	0.48	29.27_{180}	65.2 (± 6.9%)
Second serve points won (%)	56.5 ± 9.4%	46.2 ± 9.5%	0.47	42.18_{243}	76.6 (± 5.3%)
Second serve-return points won (%)[+]	53.8 ± 9.5%	43.5 ± 9.4%	0.47	42.18_{243}	76.6 (± 5.3%)
Points won of 9+ shot rally length (%)	55.6 ± 14.7%	44.4 ± 14.7%	0.35	27.57_{180}	65.7 (± 6.9%)
Winners (%)	18.1 ± 4.7%	15.1 ± 4.4%	0.31	16.67_{243}	63.9 (± 6.0%)
Break points won (%)	46.1 ± 16.0%	33.7 ± 22.5%	0.30	35.83_{230}	70.9 (± 5.9%)
Net points won (%)	67.6 ± 13.1%	61.4 ± 13.4%	0.23	22.22_{243}	61.9 (± 6.1%)
Aces (%)	5.1 ± 4.0%	3.7 ± 2.8%	0.21	10.46_{243}	59.4 (± 6.2%)
Successful first serves (%)	61.7 ± 7.4%	60.3 ± 7.2%	0.09	6.71_{243}	55.7 (± 6.2%)
Average first serve speed (km/h)	181.8 ± 9.7 km/h	180.9 ± 10.7 km/h	0.04	3.21_{180}	50.8 (± 7.3%)
Double faults (%)	3.1 ± 2.1%	3.4 ± 2.2%	-0.08	-3.09_{243}	43.9 (± 6.2%)
Unforced errors (%)	13.8 ± 4.5%	17.2 ± 5.0%	-0.34	-19.39_{243}	32.8 (± 5.9%)
Forced errors (%)	16.4 ± 3.3%	19.5 ± 3.9%	-0.40	-22.80_{243}	22.1 (± 5.2%)

[+] A player's first (or second) serve-return points won (%) = 100 – opponent's first (or second) serve points won (%), hence identical associations with match outcome.

[*] Degrees of freedom differ, as some performance characteristics (e.g. rally lengths) were only recorded on some match courts.

Table 3.4. *Women's performance characteristics (presented as mean ± sd), point-biserial correlations with match outcome, t values and PWOL values (± 95% confidence intervals); sorted by* r_{pb}.

Performance characteristic	Winning players	Losing players	r_{pb}	t_{dof}	PWOL
Baseline points won (%)	54.1 ± 7.0%	42.6 ± 7.0%	0.64	49.58_{249}	83.9 (± 4.6%)
Points won of 0-4 shot rally length (%)	55.5 ± 6.8%	44.5 ± 6.8%	0.63	39.57_{172}	84.5 (± 5.4%)
First serve points won (%)	67.5 ± 9.7%	56.1 ± 10.1%	0.50	46.83_{249}	82.8 (± 4.7%)
First serve-return points won (%)+	43.9 ± 10.1%	32.5 ± 9.7%	0.50	46.83_{249}	82.8 (± 4.7%)
Points won of 5-8 shot rally length (%)	54.8 ± 10.8%	45.2 ± 10.8%	0.41	27.25_{172}	67.8 (± 7.0%)
Second serve points won (%)	50.2 ± 11.0%	40.5 ± 10.9%	0.41	38.78_{249}	76.4 (± 5.3%)
Second serve-return points won (%)+	59.5 ± 10.9%	49.8 ± 11.0%	0.41	38.78_{249}	76.4 (± 5.3%)
Winners (%)	18.0 ± 6.1%	13.9 ± 5.2%	0.34	20.47_{249}	68.0 (± 5.8%)
Points won of 9+ shot rally length (%)	54.3 ± 16.4%	45.7 ± 16.4%	0.25	19.57_{171}	55.7 (± 7.4%)
Break points won (%)	53.7 ± 17.3%	43.0 ± 24.9%	0.24	29.64_{241}	66.0 (± 6.0%)
Aces (%)	2.7 ± 2.6%	1.7 ± 1.8%	0.23	9.47_{249}	57.2 (± 6.1%)
Net points won (%)	66.8 ± 17.5%	59.9 ± 19.1%	0.18	20.19_{249}	53.6 (± 6.2%)
Successful first serves (%)	64.5 ± 8.1%	62.8 ± 8.7%	0.10	7.83_{249}	58.0 (± 6.1%)
Average first serve speed (km/h)	155.3 ± 10.5 km/h	154.7 ± 9.9 km/h	0.03	2.13_{172}	51.7 (± 7.4%)
Double faults (%)	4.0 ± 3.2%	4.5 ± 3.4%	-0.08	-3.82_{249}	45.6 (± 6.2%)
Forced errors (%)	14.7 ± 4.1%	17.5 ± 4.0%	-0.26	-12.27_{249}	34.4 (± 5.9%)
Unforced errors (%)	15.7 ± 5.1%	19.6 ± 6.3%	-0.32	-19.81_{249}	33.6 (± 5.9%)

+ A player's first (or second) serve-return points won (%) = 100 – opponent's first (or second) serve points won (%), hence identical associations with match outcome.

Note: Degrees of freedom differ, as some performance characteristics (e.g. rally lengths) were only recorded on some match courts.

Point-biserial correlations, t values and PWOL values all identified *points won of 0-4 shot rally length*, *baseline points won* and *first serve points won* as the performance characteristics most positively associated with match outcome (i.e. success), for both sexes. *Forced errors* and *unforced errors* were the performance characteristics most negatively associated with match outcome (i.e. most strongly associated with losing). Serve-related performance characteristics including *aces*, *double faults*, *successful first serves* and *average first serve speed* were least associated with match outcome for both sexes.

3.3.1. Agreement between methods

Table 3.5. displays the Spearman's rank-order correlation coefficients (r_s) for point-biserial correlation coefficients, t values and PWOL values for men's and women's data, respectively.

Table 3.5. *Spearman's rank-order correlation coefficients for point-biserial correlation coefficients, t values and PWOL values, for both sexes.*

Pairwise comparison	Men (r_s)	Women (r_s)
r_{pb} and t	0.95	0.95
r_{pb} and PWOL	0.96	0.95
t and PWOL	0.98	0.94

Note: all correlations were significant at $p < 0.001$.

All Spearman's rank-order correlation coefficients demonstrated excellent agreement between the results of the different methods (Hahs-Vaughn & Lomax, 2012).

3.4. Discussion

The aim of this study was to establish the validity of a simple new method for identifying performance characteristics associated with success in tennis, by testing the agreement between the results of the method and those of two previously used statistical methods. Spearman's rank-order correlations between results of the new PWOL method and those of two statistical methods (paired *t*-tests and point-biserial correlations) demonstrated excellent agreement (r_s between 0.94 and 0.98; Hahs-Vaughn & Lomax, 2012), for men's and women's datasets. These high correlation values show that the PWOL method can identify performance characteristics associated with success as effectively as more complex statistical methods, and is therefore a valid alternative. Accordingly, coaches of elite players should consider employing the PWOL method, as it is simpler to calculate, interpret and contextualise than standard statistical methods.

Points won of 0-4 shot rally length demonstrated the highest PWOL value (89.0%) for men; this corresponded to a point-biserial correlation with match outcome of 0.72 and a *t* value of 44.47. In simple terms, a PWOL of 89.0% means that players who won more points of 0-4 shot rally length than their opponent won the match in almost 9 out of 10 cases. Similarly, in the women's event, *points won of 0-4 shot rally length* demonstrated the highest PWOL (84.5%), a point-biserial correlation with match outcome of 0.63 and *t* value of 39.57. So, players who won more points of 0-4 shot rally length than their opponent won the match in 84.5% of cases. *Baseline points won* and *first serve points won* were also associated with success for men and women, exhibiting PWOLs above 80%. These values corresponded to moderate point-biserial correlation coefficients and *t* values. Collectively, these results imply that *points won of 0-4 shot rally length*, *baseline points won* and *first serve points won* may be considered the three most important performance characteristics at Roland Garros, with superior performance in these areas closely associated with success for players of both sexes. These three performance characteristics all pertain to 'points won' and often comprise a large proportion of the total points played within a match, so it may be considered unsurprising that they demonstrated associations with success.

For both sexes, *forced errors* and *unforced errors* were the performance characteristics with the lowest PWOLs (between 22.1% and 34.4%), corresponding to negative point-biserial correlation coefficients and negative *t* values. For example, male players who hit more forced errors than their opponent won the match in only 22.1% of cases and female players who hit more forced errors than their opponent won the match in 34.4% of cases. These results indicate a negative association with match outcome (i.e. an association with losing), and show that hitting fewer forced and unforced errors is advantageous in terms of winning matches on clay courts.

Serve-related performance characteristics including *aces*, *double faults, average first serve speed* and *successful first serves* were among the least associated with match outcome for both sexes, exhibiting PWOL values between 43.9% and 59.4%. Together, results of the serve-related performance characteristics indicate that a player's serving performance is not closely linked with success at Roland Garros and may therefore be considered less important in terms of winning matches on clay courts.

The PWOL method has several advantages compared to standard statistical methods. Calculating the PWOL value of a performance characteristic is straightforward and the process does not require a comprehensive understanding of statistical methods or a software package. A pen, notepad and basic mobile phone calculator (if necessary) are sufficient; to tally the number of matches in which the winning player outscored the losing player on a relevant performance characteristic and calculate the tallied number of matches as a percentage of the total number of matches. Furthermore, the PWOL value of a single performance characteristic can be interpreted in isolation, whereas the result of a paired *t*-test (for example) is more difficult to contextualise, as a series of values is required to gauge relative importance. The PWOL method can also be used to help prevent 'paralysis by analysis', in that a performance analyst or future studies analysing the sport (e.g. on different surfaces) may employ the method to narrow down or filter a full list of performance characteristics and highlight those most strongly associated with success on a particular surface. The filtered list would provide a concise summary of relevant areas for coaches to focus on during training sessions.

As such, tennis analysts should consider adopting the PWOL method to investigate important performance characteristics, as its ease of interpretation means it can be effectively fed back to coaches directly (Sigrist et al., 2013). Clearly, representative tournaments should be chosen for analysis, i.e. coaches of elite female players should only consider elite level women's tournaments in their sample, rather than lower level or men's events, and court surface should also be considered. The PWOL confidence intervals displayed in Table 3.3. and Table 3.4. demonstrate that a smaller *n* resulted in a larger confidence interval. In terms of the sample size required to draw valid conclusions using the PWOL method, results suggest that analysing data from 200 matches will give confidence intervals of approximately ± 5% for PWOLs of 80 – 90%. As such, Grand Slam events are ideal for this type of analysis, as performance data from over 100 men's and women's matches are readily available to players, coaches and analysts. Further work is needed to establish whether PWOL can be used on a smaller scale (i.e. using data from fewer matches); if so, the method is such that coaches could adopt it themselves if they so wished. The process would also be efficient with an appropriately designed spreadsheet template.

In addition to its simple calculation and interpretation in a coaching context, the PWOL method offers a further benefit compared to standard statistical methods. Paired *t*-tests and point-biserial correlations both consider the magnitude of the differences between winning and losing players' values on a particular performance characteristic, when establishing that characteristic's association with match outcome. In contrast, the PWOL method simply acknowledges that the winning player's value was either higher or lower than the losing player's value, irrespective of the magnitude of the difference. For this reason, the PWOL is more robust than paired *t*-tests and point-biserial correlations in the case of extreme values and outliers. For example, in this study, men's *average first serve speed* exhibited a *t* value of 3.21, which indicates a *significant* difference between winning and losing players' values. However, if we were to remove from the dataset the *two* matches in which the lowest average first serve speeds occurred, the *t* value would decrease to a *non-significant* 1.76, which demonstrates the strong influence of extreme values in a paired *t*-test. While PWOL may be more robust to outliers (by disregarding the magnitude of the difference between two players' values), it should be noted that in some instances, the magnitude of the difference can offer relevant information.

The PWOL method is proposed as a more user-friendly alternative for coaches, so statistical significance was not incorporated in the results here, as it is unlikely to be relevant in a coaching context. It is worth highlighting, however, that if performance analysts or other users wish to calculate statistical significance for PWOL values, this can be done using a binomial distribution, with parameters n and *p*, where n is the sample size and *p* is the probability of, in this case, the winning player outscoring the losing player in a single match.

In previous studies attempting to identify performance characteristics associated with success in tennis (O'Donoghue, 2002; Reid et al., 2010), methodological differences such as the performance characteristics included, and their respective calculations appear to have contributed to inconsistent results. For example, rally length statistics have not previously been included, but here, *points won of 0-4 shot rally length* was the characteristic most strongly associated with success. This study has shown that the PWOL method, correlation-based method and paired *t*-test method demonstrate excellent pairwise agreement. Therefore, if performance characteristics, operational definitions and analysis methods are consistent between studies in the future, it can be assumed that any differences in the characteristics identified as strongly associated with success are attributable to differences in the context of the performances analysed (e.g. court surface, sex, time etc.), and not methodological differences. The list of performance characteristics presented here comprises a more comprehensive selection than those analysed in previous studies. Future research aiming to identify performance characteristics associated with success in tennis should endeavour to incorporate a comprehensive range of characteristics, including rally length statistics. Accordingly, a standardised list of tennis strategy performance characteristics, calculations and definitions would be beneficial.

3.5. Conclusion

In summary, results of the PWOL method demonstrated excellent agreement with results of the point-biserial correlation and paired *t*-test methods. As such, this study has shown that the PWOL method is able to successfully identify performance characteristics associated with success in elite tennis. The method is simple to calculate and does not require statistical software or the expertise of a performance analyst to interpret the results; this may encourage tennis players and coaches to begin to engage with performance analysis as a scientific discipline and recognise its potential benefits. Furthermore, the PWOL method is robust in the case of extreme values. The PWOL method is therefore proposed as a suitable, more user-friendly alternative to common statistical methods of data analysis in elite tennis.

Chapter 4

Acquiring, cleaning and assessing the reliability of grass court tennis match-play data

This chapter describes the process undertaken to identify and access an appropriate source of elite level, grass court tennis match-play data. Detail regarding the nature of data obtained (i.e. list of performance characteristics, number of matches) is provided, and the procedures performed by a Grand Slam data entry team to ensure rigour are described. The data cleaning method is also outlined, before the inter-rater reliability of the data is assessed, using Cohen's kappa.

4.1. Locating and acquiring appropriate data

Players are able to access match-play performance data via official tournament channels, but the ownership of and access to such data can be problematic for those wishing to undertake empirical research. Globally, tennis is led by four primary governing bodies: the Association of Tennis Professionals (ATP), the Women's Tennis Association (WTA), the International Tennis Federation (ITF), and the Grand Slam Board (Conrad, 2017), each of which presides over a specific set of tournaments. Additionally, many countries have a national governing body (e.g. Great Britain's Lawn Tennis Association), responsible for the running of national and international tennis events hosted by that nation. As a result, there is little consistency in the match-play data collection practices employed, as different tournaments recruit different performance analysis and technology companies. Additionally, as national governing bodies typically fund their own elite player performance programmes, it is in their interests to restrict access to any match-play data that they own, to prevent players from other countries from potentially benefitting. Therefore, it can be challenging and time consuming to obtain access to reliable tennis match-play datasets.

Based on the limited amount of grass court tennis research highlighted in the literature review, a list of potential sources of grass court match-play data was compiled. Table 4.1. displays the list, alongside details of the data potentially available and progress made (including whether access was granted).

Table 4.1. *Grass court tennis data sources and other relevant information.*

Data source	Players	Data details	Initial contact	Response?	Progress
IBM Wimbledon	All	Wimbledon singles match-play data. Player profile data?	Oct-17	Yes	IBM agreed in principle to share data. August 2018: **Access granted**.
Tennis Analytics	Juniors	Junior Wimbledon match-play data	Nov-17	Yes	Agreed to share data, with NDA, if they can use results.
ITF	Juniors	Junior Grand Slam singles match-play data? Spin data?	Dec-17	Yes	No access given (impartiality)
SAP (WTA provider)	Women	WTA grass court events	Nov-17	No	IBM suggest response is unlikely.
Infosys (ATP provider)	Men	Serve & return data by surface, available online but only includes annual summary data	N/A - online	N/A	N/A - insufficient sample (only summary data)
IBM Preview	Men & Women	Wimbledon singles finals match reports from 2001-2017	Oct-17	Yes	Obtained annual sample data (finals) from 2014, 2016 & 2017.
LTA Hawk-Eye	Men & Women	Grand Slam player- & ball-tracking data (matches involving Brits)	Nov-17	Yes	In contact, but limited matches - insufficient sample size
Hawk-Eye	Men & Women	Full Grand Slam player- & ball-tracking data	Jul-18	Yes	Likely to gain access, may take time. April 2019: **Access granted.**
TennisAbstract .com	Men & Women	Match-play data all surfaces (sample is sporadic & potentially unreliable as compiled by public)	N/A - online	N/A	N/A - reliability questionable and inconsistent sample.

Despite grass court match-play data being available from several sources, the sample of matches and number of performance characteristics were often limited (see Table 4.1. for details). For example, the Lawn Tennis Association's (LTA) dataset only included matches involving British players, and Infosys only presented annual summary data of serve and serve-return characteristics online. Additionally, with little information available regarding how some datasets had been collated, their reliability and validity were unclear. For example, the TennisAbstract.com dataset was compiled by members of the public over time, with no measures employed to ensure consistency, validity or reliability. After consideration, sourcing official match-play data directly from Wimbledon was prioritised, as the grass court Grand Slam is widely regarded as the most important event of the tennis calendar (Gourville & Arnold, 2017) and as Wimbledon's dataset was likely to be among the most reliable, due to their thorough data collection and management processes (detailed in Section 4.2.1.).

International Business Machines (IBM) are responsible for recording and storing Wimbledon match-play data, so the researcher initiated contact with IBM's Wimbledon Client and Programme Executive. Following discussions, an agreement was made in principle, to share Wimbledon's match-play data, pending approval from the Wimbledon IT Director. After receiving written approval, a data sharing agreement between the All England Lawn Tennis Club and the Centre for Sports Engineering Research at Sheffield Hallam University was drafted and signed by all parties. Ten months after first contact, access to the data was granted.

4.2. Method

4.2.1. Wimbledon's data collection process

All data were recorded live by trained courtside data collectors. To be considered for the Wimbledon data entry team, individuals are required to undertake an interview followed by further assessment, attend compulsory familiarisation and training sessions at Wimbledon over a 3-month period, attend mandatory qualifying and main draw dress rehearsal days, and have considerable tennis playing experience and excellent knowledge of the sport (Wimbledon, 2019). Data collectors are provided with official documentation detailing all operational definitions and accurate tennis terminologies (IBM, 2020), to facilitate objectivity and consistency across the data entry team (Hughes et al., 2004). All recorded data are subject to random checks and annual reliability testing procedures carried out by IBM. These rigorous processes help to ensure the quality and accuracy of all data collected.

4.2.2. Performance characteristics

With institutional ethics approval, match-level data for Wimbledon main draw singles matches contested between 1992 and 2017 (n = 5967 matches) were obtained from IBM's (2019) Wimbledon Information System. The following performance characteristics were obtained for winning and losing players in each match (for a full list of definitions, see Appendix A):

- number of aces, number of double faults
- number of first serves attempted, number of first serves in
- number of serve-volley points played, number of serve-volley points won
- number of first serve points won, number of second serve points won
- number of first serve-return points won, number of second serve-return points won
- number of baseline points won, number of net points won
- number of forehand and backhand winners, number of forehand and backhand forced errors, number of forehand and backhand unforced errors
- total number of points played, total number of points won.
- number of points played and won of 0-4, 5-8 and 9+ shot rally length*, respectively, and average (i.e. mean) first serve speed were obtained for matches where a serve speed radar was available.

* The rally length of a point is comprised only of successful strokes (i.e. strokes whereby the ball crosses the net, to the side of the opponent, and lands inside the court); errors are not counted.

Despite the rigorous procedures and checks undertaken by IBM and Wimbledon, as these are secondary data (i.e. not collected by the researcher), their reliability must be assessed independently (Verma, 2012). Secondary data are also more likely to contain errors and outliers than primary data, so the data must be cleaned and error detection processes undertaken before valid conclusions can be drawn (Verma, 2012).

4.2.3. Data cleaning process

Several stages of data cleaning were undertaken by the researcher. First, data from incomplete matches (i.e. those involving retirements, walkovers or defaults) were identified and removed from the dataset. This reduced the total number of matches from 5967 to 5818. Then, the data for each performance characteristic were plotted and checked for outliers and extreme values. Several comparisons between performance characteristics were also made to ensure consistency. For example, the number of points played of 0-4, 5-8 and 9+ shot rally length in a single match should sum to the total number of points played in that match. Data were also checked to establish whether the values recorded for each performance characteristic were within an 'acceptable' range. The definition of this differed for each performance characteristic, and was based on simple logic, the rules of tennis (International Tennis Federation, 2020b), previous research and the researcher's knowledge of the sport. For example, the world's fastest tennis serve speeds were recorded as 163.4 miles per hour (mph) for a male player and 136.7 mph for a female player (Tennis Companion, 2020), and serve speeds below 60 mph are extremely rare; therefore, average first serve speeds between 60 mph and 140 mph (for women) and between 70 mph and 165 mph (for men) were considered acceptable. Additional logical checks were carried out, such as ensuring that the number of net points won and the number of baseline points won by a single player in a match were both equal to or lower than the total number of points won by that player. Similarly, the number of points won by the winning player in a match should equal the total number of points played in the match minus the number of points won by the losing player. After all checks were complete and erroneous data removed, data from 5669 matches remained.

4.2.4. Inter-rater reliability testing

To enable inter-rater reliability testing between the researcher and Wimbledon's data entry team, video footage of a random selection of matches was required. IBM retain only one copy of each match and do not share these data, so other potential sources of video data, such as the internet, the British Broadcasting Corporation (BBC) and the LTA, were explored. Footage from several internet sources was deemed to be of insufficient quality, with inconsistent camera angles, poor image resolution and/or incomplete matches. Accessing BBC footage was not viable due to the associated time, cost and logistics. However, the LTA own video footage of many Wimbledon matches contested between 2013 and 2017. As such, with their permission, video recordings of ten randomly selected matches (one men's match and one women's match per year between 2013 to 2017) were obtained, observed and coded independently by the researcher, using a NacSport (NacSport Elite, Las Palmas de Gran Canaria, Spain) custom-notational analysis system. It was not possible to assess the reliability of any Wimbledon match-play data collected prior to 2013, as video footage was not available.

The data coded by the researcher were summarised at match level before being compared to the match-level data collated by Wimbledon's data entry team. Cohen's kappa is a statistic for quantitatively measuring the agreement between two observers who each classify n items into c categories, corrected for the number of occasions when the observers may agree by chance (McHugh, 2012). For this reason, it is widely-used to measure the reliability of datasets in sports performance analysis (O'Donoghue, 2013). Using Equation 4.1, a k value between -1 and +1 is produced, with $k = 1$ indicating perfect agreement, $k = 0$ indicating random agreement and $k < 0$ indicating less agreement than random chance:

Equation 4.1.

$$k = \frac{(P_o - P_e)}{(1 - P_e)}$$

where P_o represents the actual observed agreement (absolute agreement / total observations), and P_e represents chance agreement (total expected agreement / total observations).

Table 4.2. displays sample data from a single match coded by two observers (the researcher and a member of Wimbledon's data entry team), as well as relevant values for calculating Cohen's kappa coefficient. For a detailed discussion on Cohen's kappa, including a sample step-by-step calculation, see McHugh (2012).

Table 4.2. *Sample data from one match coded by the researcher and Wimbledon's data entry team, with relevant values for calculating Cohen's kappa.*

Performance characteristic	Observer 1 (researcher)	Observer 2 (data entry team)	Absolute difference	Expected agreement
Number of successful first serves	94	94	0	9.0
Number of first serves attempted	153	153	0	24.0
Number of successful second serves	58	58	0	3.4
Number of double faults	5	5	0	0.0
Number of aces	11	11	0	0.1
Number of first serve points won	60	60	0	3.7
Number of second serve points won	34	34	0	1.2
Number of first serve-return points won	34	34	0	1.2
Number of second serve-return points won	25	25	0	0.6
Number of baseline points won	67	66	1	4.5
Number of baseline points lost	83	81	2	6.9
Number of net points won	32	32	0	1.0
Number of net points lost	17	17	0	0.3
Number of winners	35	35	0	1.3
Number of forced errors	62	64	2	4.1
Number of unforced errors	37	38	1	1.4
Number of points won of 0-4 shots	115	114	1	13.4
Number of points won of 5-8 shots	33	34	1	1.1
Number of points won of 9+ shots	4	4	0	0.0
Number of break points won	6	6	0	0.0
Number of break points played	12	12	0	0.1
Total observations	977	977	8	77.4

$$\frac{(\text{Observer 1} * \text{observer 2})}{\text{total observations}}$$

$$\frac{(94 * 94)}{977} = 9.0$$

Absolute agreement = total observations – total absolute difference

977 – 8 = 969

Total expected agreement

Total observations

Total absolute difference

In the single match sample provided in Table 4.2,

$P_o = (969 / 977) = 0.992$

$P_e = (77.4 / 977) = 0.079$

Therefore,

$$k = \frac{(0.992 - 0.079)}{(1 - 0.079)} = \mathbf{0.991}$$

Cohen's kappa coefficient, calculated for all performance characteristics except first serve speed, based on analysis of over 1400 match-play points (n = 10 matches), was k = 0.99, identified as excellent (Fleiss, 1981). It was not possible to assess the reliability of first serve speed, as measured by Wimbledon's serve speed radar system. Wimbledon's Doppler radar unit measures the speed of a tennis ball by detecting a frequency change in the returned radar signal caused by the Doppler effect, whereby any increase (or decrease) in the returned frequency is proportionate to the ball's increase (or decrease) in approach speed (Maquirriain et al., 2016). Although no published research has assessed the reliability of the Doppler radar unit, the system is in place at all four Grand Slams and several tour events (Clarey, 2012), which facilitates consistency and implies its acceptance as a measure of serve speed within professional tennis.

As such, the IBM Wimbledon dataset was deemed sufficiently reliable for the studies in this thesis. The dataset will therefore be analysed to identify important performance characteristics in elite grass court tennis over time (Chapter 5), in close and one-sided matches (Chapter 6) and in relation to the clay-to-grass court surface transition (Chapter 7).

Chapter 5

Identifying the most important performance characteristics at Wimbledon: a longitudinal perspective

In Chapters 3 and 4, the PWOL method was validated and the reliability of Wimbledon match-play data established. This chapter presents the performance characteristics of men's and women's match-play at Wimbledon between 1992 and 2017, and uses the PWOL method to establish the importance of each characteristic in terms of winning elite grass court tennis matches.

5.1. Introduction

It is well documented that tennis has lagged behind many other sports in its use of notational analysis data to enhance performance (Martin et al., 2012). Despite a recent drive to change this (e.g. Reid et al., 2016; Krause et al., 2018; Kovalchik & Reid, 2018; Cui et al., 2020), issues still remain. Firstly, although several studies have investigated hard court tennis (e.g. Reid et al., 2016; Kovalchik & Reid, 2017; Cui et al., 2020) and clay court tennis (e.g. Fernandez-Fernandez et al., 2009; Costa Pereira et al., 2017), few have focused on grass court tennis. Several analyses have included grass court match-play data (e.g. Brown & O'Donoghue, 2008; O'Donoghue & Brown 2008; Cross, 2014; Carboch, 2017), but their aims were typically to compare the four Grand Slams (i.e. on different court surfaces), rather than focusing on grass court tennis. It is important to address the lack of grass court specific research, to ensure coaches and practitioners can access relevant, up-to-date information and associated recommendations, to support their work with elite players in preparation for and during the grass court season. Another problem with tennis notational analysis literature is the lack of comprehensive longitudinal studies. Analysing longitudinal, grass court match-play data may reveal patterns and/or trends in the data, indicate how the sport has changed and may change in the future, and in turn, facilitate several practical applications.

Establishing the performance characteristics of elite grass court tennis is important to inform coaching practice, but the practical relevance of these data alone is limited. Understanding which performance characteristics are associated with success, however, is of greater practical relevance (Choi et al., 2008). For example, while it may be useful for coaches to know that men's mean first serve speeds have increased over time (Cross & Pollard, 2009), it would be more prudent to investigate whether this change had implications for winning matches. Establishing whether individuals with higher first serve speeds experience more success would help coaches to determine whether they should focus on increasing their player's serve speed. In this context, few studies have considered which performance characteristics are important in terms of winning tennis matches. Such practically relevant research is crucial for informing coaches and other practitioners which aspects of match-play should be afforded focus during training and preparation for tournaments.

This study presents the performance characteristics of men's and women's Wimbledon match-play between 1992 and 2017. The aim was to establish the importance of each performance characteristic in terms of winning grass court tennis matches.

5.2. Method

5.2.1. Matches

With institutional ethics approval, performance characteristics for men's and women's Wimbledon singles matches contested between 1992 and 2017 (men n = 2898, women n = 2920) were obtained from the Wimbledon Information System (IBM, 2019). Access to the data was provided by IBM, with permission granted by The All England Lawn Tennis Club. It was not possible to obtain performance characteristics for every match played during the 26-year time period, as prior to 1997, match-play data were only recorded on a selection of courts. Additionally, several performance characteristics were introduced later than 1992 (e.g. 'serve-volley points' were recorded from 1997 onwards, and in 1998, 'forced errors' were introduced; all errors had previously been recorded as 'unforced errors'). Data from incomplete matches (i.e. those involving retirements, walkovers or defaults) were excluded; 104 men's matches and 45 women's matches were excluded accordingly.

5.2.2. Performance characteristics

The following performance characteristics were obtained for the winning and losing player in each match (for a full list of definitions, see Appendix A):

- number of aces, number of double faults
- number of first serves attempted, number of first serves in
- number of serve-volley points played, number of serve-volley points won
- number of first serve points won, number of second serve points won
- number of first serve-return points won, number of second serve-return points won
- number of baseline points won, number of net points won
- number of forehand and backhand winners, number of forehand and backhand forced errors, number of forehand and backhand unforced errors
- total number of points played, total number of points won
- number of points played and won of 0-4, 5-8 and 9+ shot rally length, respectively, and average (i.e. mean) first serve speed were obtained for matches where a serve speed radar was available.

The inter-rater reliability of all performance characteristics except first serve speed, assessed using Cohen's kappa, was $k = 0.99$, defined as excellent (Fleiss, 1981; for details of reliability testing, see Chapter 4).

5.2.3. Data processing and analysis

All data were cleaned (for details, see Chapter 4) then stratified by sex and year. To establish the performance characteristics over time for men and women, data were normalised at match level using the calculations in Table 5.1., before being reduced to mean values per year. For the purpose of calculating the *Percentage of matches in which the Winner Outscored the Loser* (PWOL), the data were also stratified by match outcome (i.e. winning player or losing player) before being normalised and reduced to mean values. The winning player's performance was then compared to that of their opponent (i.e. the losing player) at match level for each performance characteristic, to identify which player 'outscored' the other, allowing the PWOLs to be calculated. The PWOL method was developed as a more user-friendly alternative (to point-biserial correlations and paired *t* tests) to facilitate coaches’ understanding of match-play data analysis; for a detailed validation against Student’s t-tests and point biserial correlation methods, see Chapter 3.

Table 5.1. *Normalised performance characteristic calculations for Wimbledon, derived from O'Donoghue and Ingram (2001) and O'Donoghue (2005).*

Performance characteristic	Calculation
Aces (%)	Number of aces/number of serves performed x 100
Double faults (%)	Number of double faults/number of points served x 100
Successful first serves (%)	Number of first serves in/number of first serves attempted x 100
First serve points won (%)	Number of first serve points won/number of first serve points played x 100
First serve-return points won (%)	Number of first serve-return points won/number of first serve-return points played x 100
Second serve points won (%)	Number of second serve points won/number of second serve points played x 100
Second serve-return points won (%)	Number of second serve-return points won/number of second serve-return points played x 100
Serve-volley points played (%)	Number of serve-volley points played/number of serve points played x 100
Serve-volley points won (%)	Number of serve-volley points won/number of serve-volley points played x 100
Net points played (%)	Number of net points played/number of rally points played x 100
Net points won (%)	Number of net points won/number of net points played x 100
Baseline points played (%)	Number of baseline points played/number of rally points played x 100
Baseline points won (%)	Number of baseline points won/number of baseline points played x 100
Winners (%)	Number of winners/number of rally points played x 100
Forced errors (%)	Number of forced errors/number of rally points played x 100
Unforced errors (%)	Number of unforced errors/number of rally points played x 100
Forehand winners (%)*	Number of forehand winners/total number of groundstroke winners x 100
Backhand winners (%)*	Number of backhand winners/total number of groundstroke winners x 100
Points won of 0-4 rally length (%)	Number of points won of 0-4 rally length/number of points played of 0-4 rally length x 100
Points won of 5-8 rally length (%)	Number of points won of 5-8 rally length/number of points played of 5-8 rally length x 100
Points won of 9+ rally length (%)	Number of points won of 9+ rally length/number of points played of 9+ rally length x 100

* Calculations for forehand/backhand forced errors and forehand/backhand unforced errors replicate those for forehand/backhand winners.

It is important to note that the PWOL for any particular performance characteristic has larger confidence intervals than the associated mean value. So, although a year-to-year change of, for example, 2% in the mean percentage of *aces* may be considered meaningful, a year-to-year change of 5% in the PWOL for *aces* may not be meaningful.

PWOL interpretation is defined in Table 5.2. PWOL figures in the results section are shaded to aid interpretation.

Table 5.2. *PWOL interpretation.*

PWOL	Interpretation
80% ≤ PWOL ≤ 100%	Strong association with winning
60% ≤ PWOL < 80%	Association with winning
40% ≤ PWOL < 60%	No association with match outcome
20% ≤ PWOL < 40%	Association with losing
0% ≤ PWOL < 20%	Strong association with losing

Finally, to summarise and prioritise results from recent match-play, which are likely to be most relevant to coaches and practitioners, data from the three most recent (available) years were combined to calculate the PWOL for each performance characteristic between 2015 and 2017.

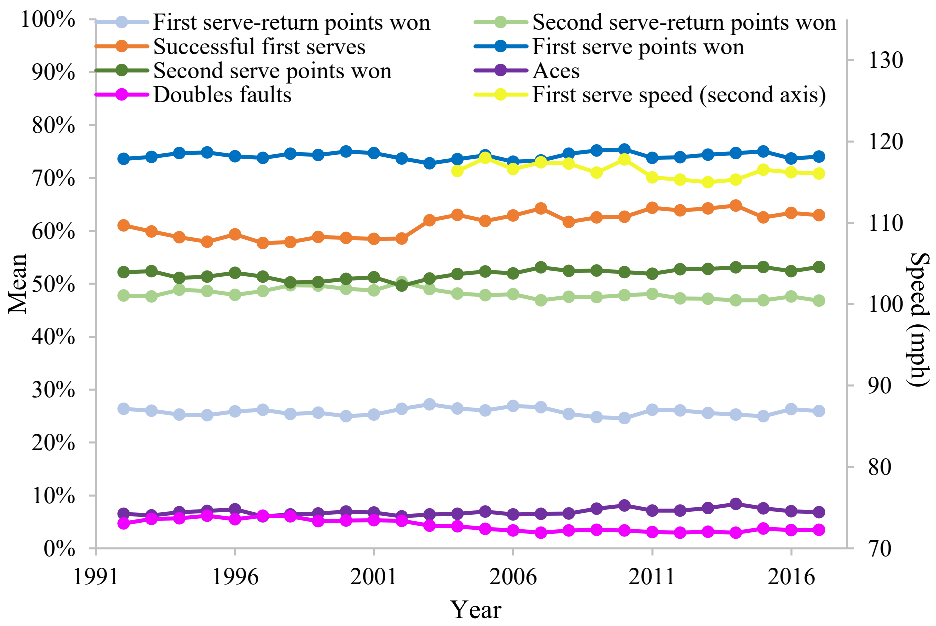
5.3. Results

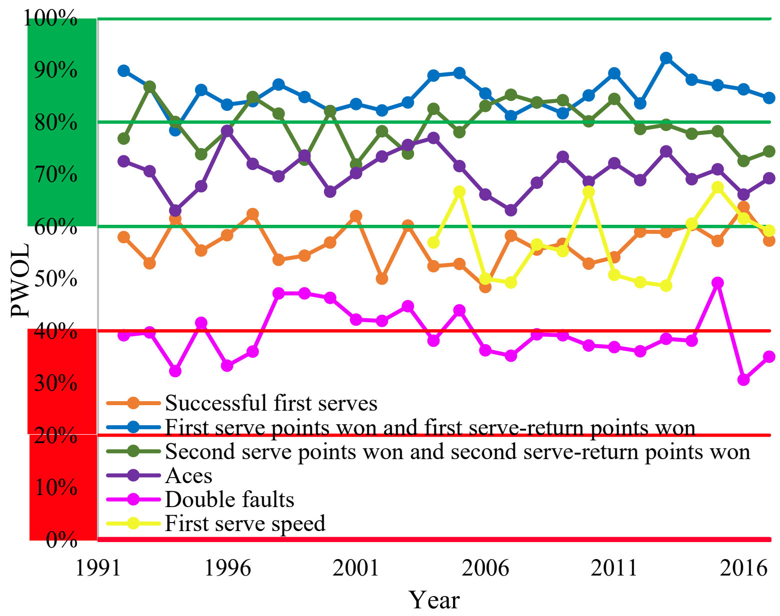
Results are presented in three subsections. First, men's longitudinal analysis (Section 5.3.1.) is presented for all performance characteristics, alongside associated PWOLs (Figures 5.1. to 5.5.). Then, women's longitudinal analysis (Section 5.3.2.) is presented for all performance characteristics, alongside associated PWOLs (Figures 5.6. to 5.10.). Finally, the PWOLs for men's and women's performance characteristics aggregated over recent years (i.e. between 2015 and 2017) are displayed in Table 5.3. (Section 5.3.3.), to reflect recent match-play and facilitate up-to-date practical recommendations.

5.3.1. Men's longitudinal analysis

Figures 5.1a. and 5.1b. display men's mean serve-related performance characteristics over time and associated PWOLs, respectively.

Figure 5.1.





a) *Men's mean serve-related performance characteristics from 1992 to 2017.*

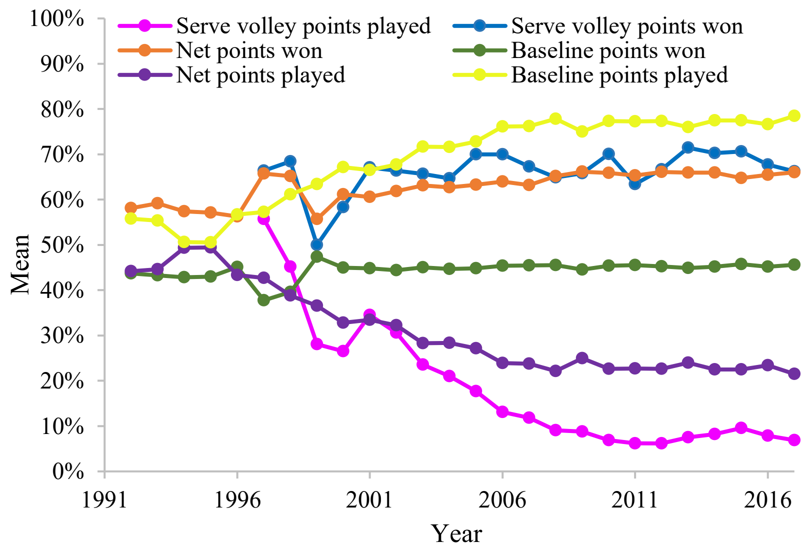
b) *PWOLs for men's serve-related characteristics from 1992 to 2017.*

Figure 5.1a. shows that, of all men's serve-related performance characteristics, *successful first serves* exhibited the greatest amount of change over time, increasing by 6.3% between 2002 and 2014. Men consistently won a higher percentage of *first serve points* than *second serve points*, and *aces* were typically more prevalent than *double faults*, particularly from 2003 onwards. *First serve speed* peaked at 118.0 mph in 2005.

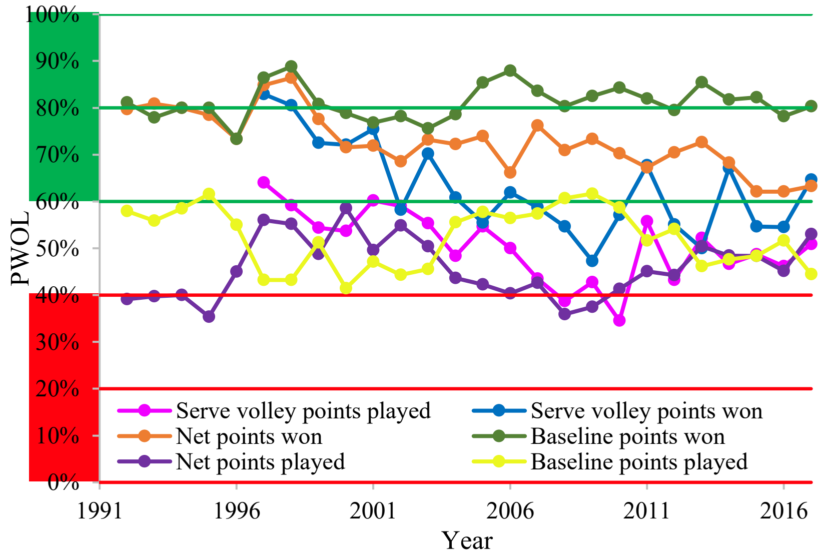
Figure 5.1b. shows that men's *first serve points won* and *first serve-return points won* were more strongly associated with winning matches than all other serve-related performance characteristics, with PWOL remaining above 80% in all years except one (1994). *Second serve points won*, *second serve-return points won* and *aces* were also associated with winning matches. With PWOL often between 40% and 60%, *successful first serves* and *first serve speed* were typically not associated with match outcome.

Figures 5.2a. and 5.2b. display men's mean net-play and baseline play characteristics over time and associated PWOLs, respectively.

Figure 5.2.



a) *Men's mean net and baseline play characteristics from 1992 to 2017.*



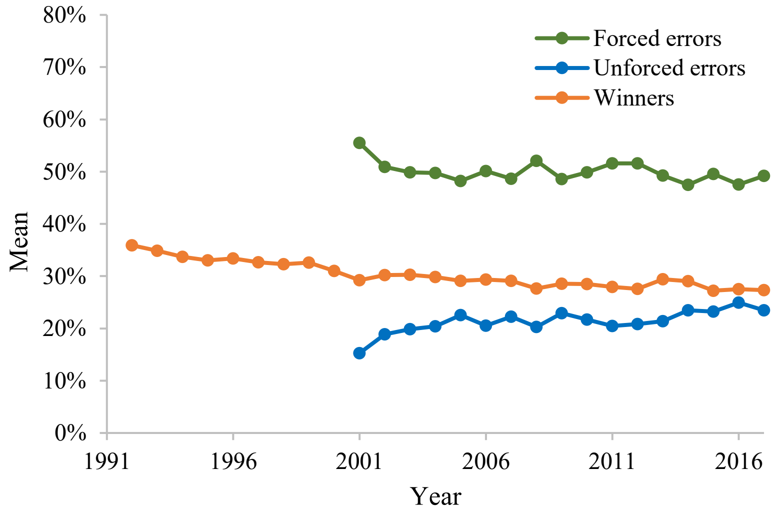
b) *PWOLs for men's net and baseline play characteristics from 1992 to 2017.*

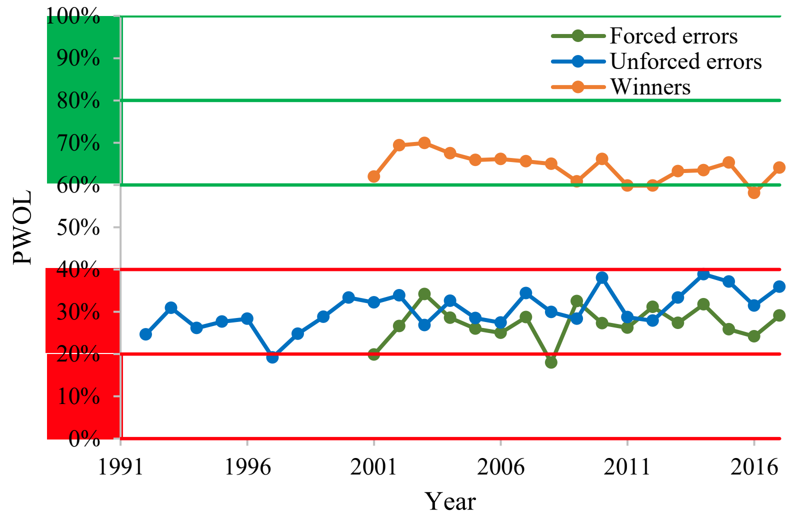
Figure 5.2a. shows that men's *serve-volley points played* decreased from a peak of 55.7% in 1997 to a low of 6.2% in 2011. *Net points played* also decreased during this time, whereas *baseline points played* increased. The percentage of *net points played* and *serve-volley points played* were consistently lower than the percentage of *baseline points played*, however the percentage of *net points won* and *serve-volley points won* were consistently higher than the percentage of *baseline points won*.

Figure 5.2b. shows that, in the 1990s, *net points won* and *baseline points won* were strongly associated with winning matches, with PWOL often exceeding 80%. From 1999 onwards, the PWOL for *net points won* dropped to between 60% and 80%, whereas the PWOL for *baseline points won* remained close to 80%. The PWOL for *serve-volley points won* was above 80% in 1997 and 1998, but subsequently decreased, reaching a low of 47% in 2009. *Serve-volley points played* exhibited a PWOL above 60% in 1997, but in most subsequent years, this characteristic was not associated with match outcome, with PWOL between 40% and 60%.

Figures 5.3a. and 5.3b. display men's mean point-ending performance characteristics over time and associated PWOLs, respectively.

Figure 5.3.





a) *Men's mean point-ending performance characteristics from 1992 to 2017.*

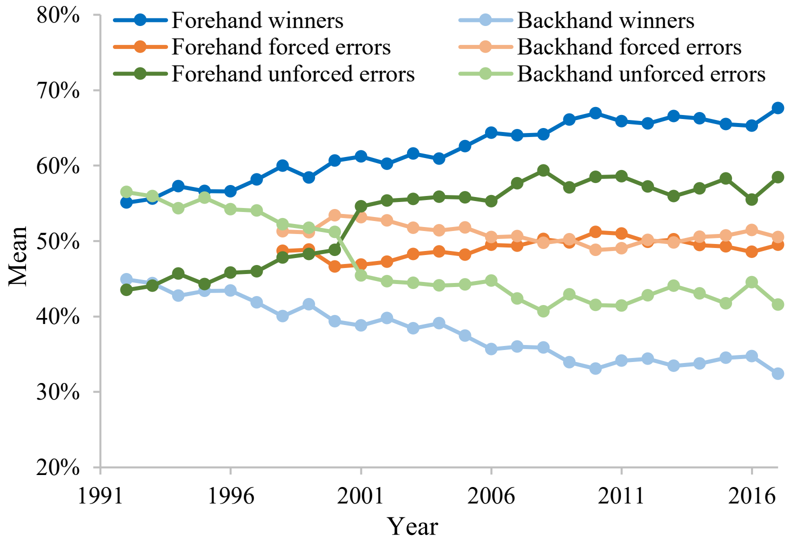
b) *PWOLs for men's point-ending characteristics from 1992 to 2017.*

Figure 5.3a. shows that *forced errors* has been the most prevalent point-ending characteristic since their introduction in 2001. *Winners* decreased over time, from 36.0% in 1992 to 27.4% in 2017. *Unforced errors* tended to increase over time, from 15.3% in 2001 to 23.4% in 2017, and *forced errors* decreased from a high of 55.5% in 2001 to 48.2% in 2005.

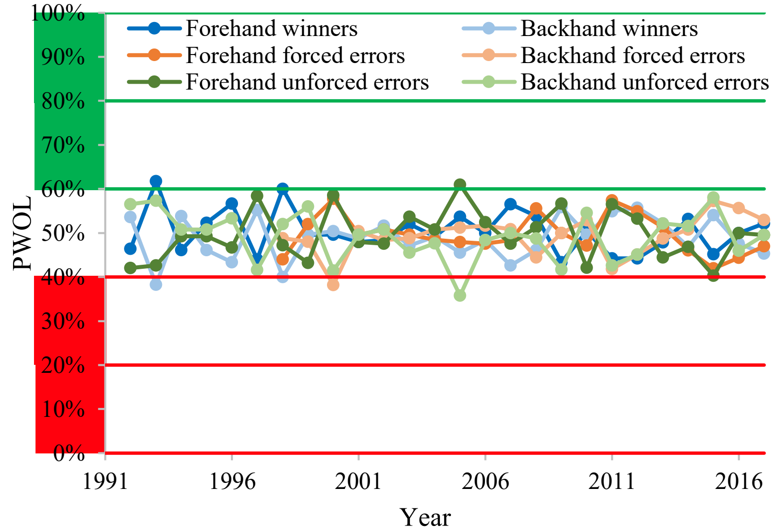
Figure 5.3b. shows that, for men, *winners* were associated with winning matches, with PWOL typically between 60% and 80%, whereas *forced errors* and *unforced errors* were associated with losing matches, with PWOL typically between 20% and 40%.

Figures 5.4a. and 5.4b. display men's mean point-ending characteristics, stratified by groundstroke (i.e. forehand/backhand), over time and associated PWOLs, respectively.

Figure 5.4.



a) *Men's mean forehand and backhand point-ending performance characteristics from 1992 to 2017.*



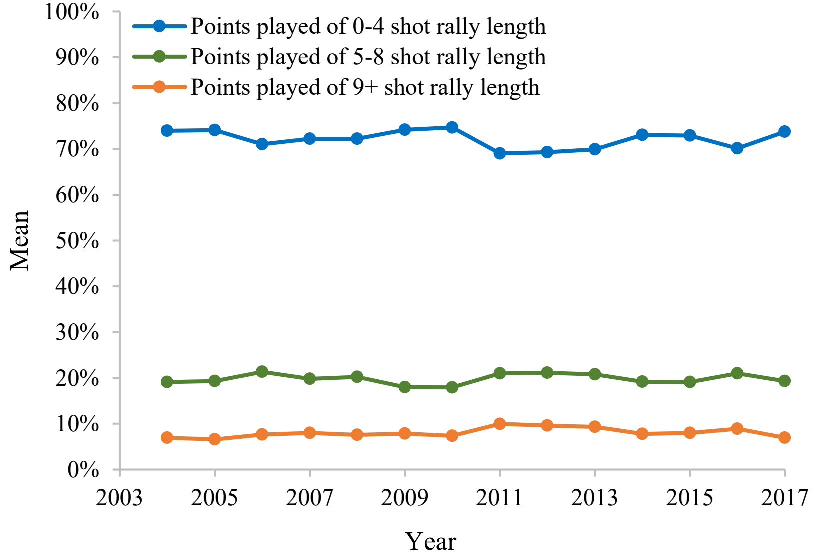
b) *PWOLs for men's forehand and backhand point-ending characteristics from 1992 to 2017.*

Figure 5.4a. shows that men's *forehand winners* increased from 55.1% in 1992 to 67.6% in 2017; *forehand unforced errors* also increased during this time, from 43.5% to 58.5%. Correspondingly, *backhand winners* and *backhand unforced errors* decreased during the same time period. *Forehand winners* were more prevalent than *backhand winners* throughout, and the difference between the two increased over time. Prior to 2001, *backhand unforced errors* were more prevalent than *forehand unforced errors*, but from 2001 onwards, *forehand unforced errors* were more prevalent.

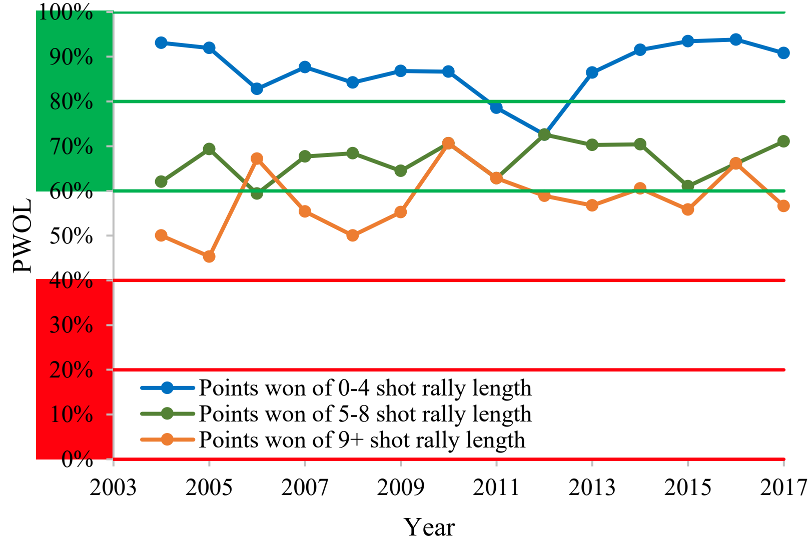
Figure 5.4b. shows that, for men, none of the six forehand and backhand point-ending performance characteristics were associated with match outcome, with PWOLs remaining between 40% and 60%, in almost all cases.

Figures 5.5a. and 5.5b. display men's mean percentage of points played of each rally length over time, and associated PWOLs, respectively.

Figure 5.5.



a) *Men's mean percentage of points played of each rally length, from 2004 to 2017.*



b) *PWOLs for men's percentage of points won of each rally length, from 2004 to 2017.*

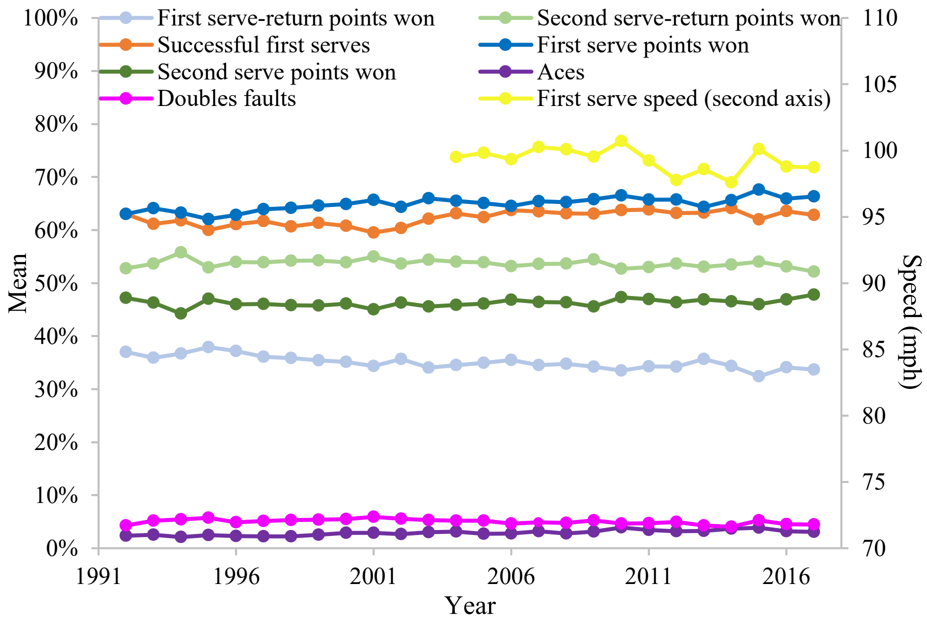
Figure 5.5a. shows that, for men, *points played of 0-4 shot rally length* were more prevalent than *points played of 5-8 shot rally length* and *points played of 9+ shot rally length*; in turn, *points played of 5-8 shot rally length* were more prevalent than *points played of 9+ shot rally length*. Despite small fluctuations, the percentage of points played of all three rally lengths remained relatively consistent over time.

Figure 5.5b. shows that of the three rally lengths, *points won of 0-4 shot rally length* was the most strongly associated with winning matches for men, with PWOL above 80% in almost all cases, and exceeding 90% six times. *Points won of 5-8 shot rally length* was associated with winning matches, with PWOL remaining between 60% and 80% throughout. *Points won of 9+ shot rally length* often exhibited no association with match outcome.

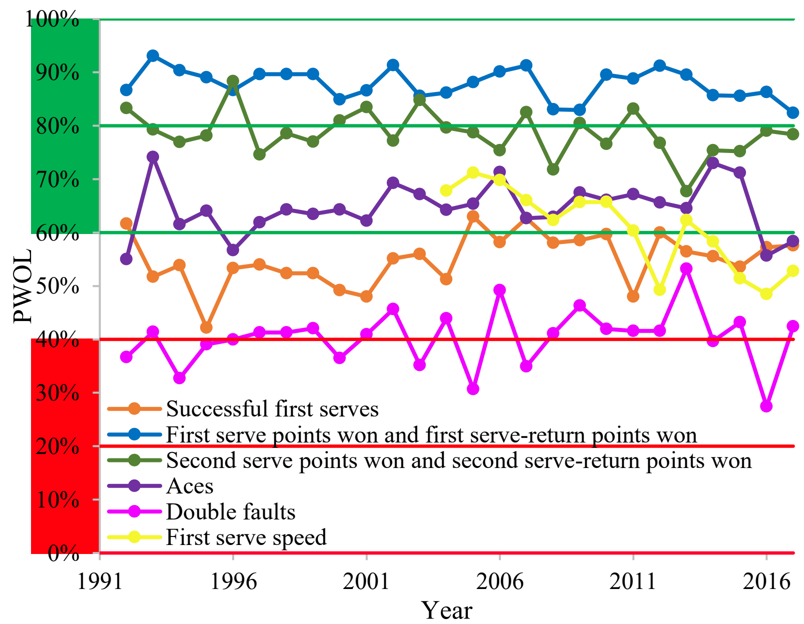
5.3.2. Women's longitudinal analysis

Figures 5.6a. and 5.6b. display women's serve-related performance characteristics over time and associated PWOLs, respectively.

Figure 5.6.



a) *Women's mean serve-related performance characteristics from 1992* to 2017.



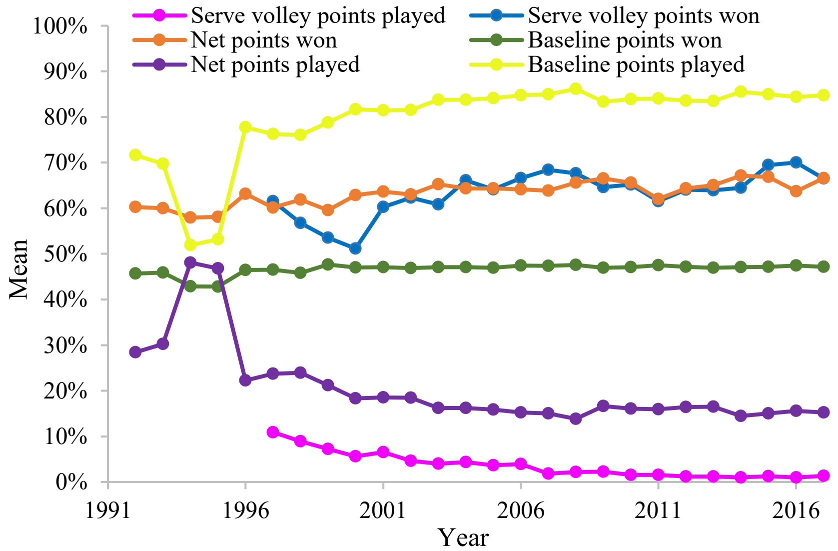
b) *PWOLs for women's serve-related characteristics from 1992 to 2017.*

Figure 5.6a. shows that women's *first serve points won* increased from 62.1% in 1995 to 65.7% in 2001. *Successful first serves* increased from a low 59.5% in 2001 to a peak of 64.1% in 2014. Women consistently won a higher percentage of *first serve points* than *second serve points*. *Double faults* were typically more prevalent than *aces*, and *first serve speed* peaked at 100.7 mph in 2010.

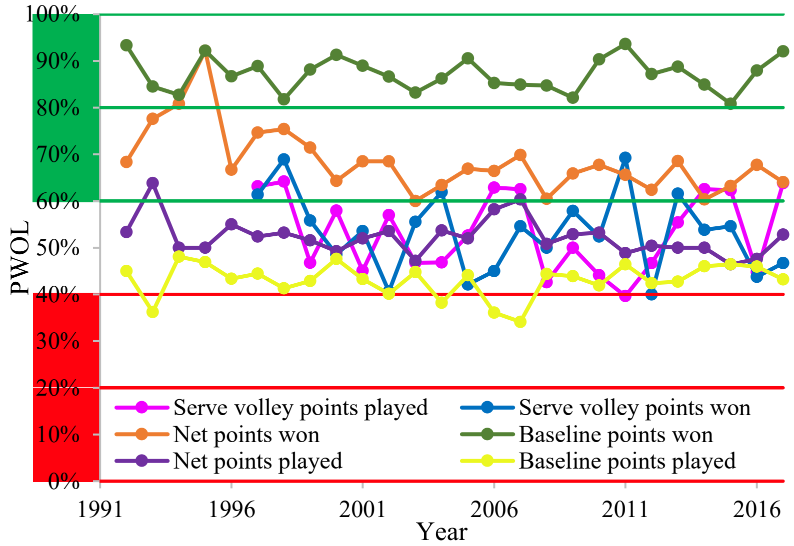
Figure 5.6b. shows that, with PWOL remaining above 80% throughout, women's *first serve points won* and *first serve-return points won* were strongly associated with winning matches. *Second serve points won*, *second serve-return points won* and *aces* were also associated with winning. *First serve speed* was associated with winning between 2004 and 2011, but was not typically associated with match outcome after 2011. *Successful first serves* was not typically associated with match outcome, and *double faults* fluctuated between an association with losing and no association with match outcome.

Figures 5.7a. and 5.7b. display women's net-play and baseline play characteristics over time and associated PWOLs, respectively.

Figure 5.7.



a) *Women's mean net and baseline play characteristics from 1992 to 2017.*



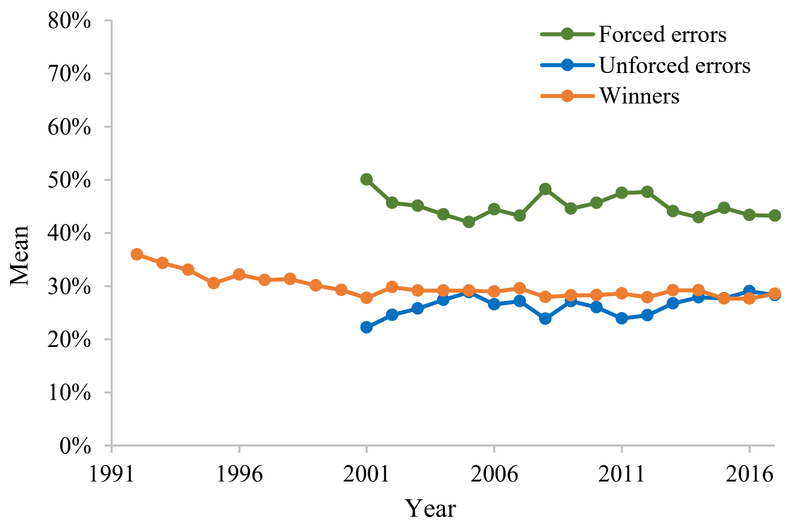
b) *PWOLs for women's net and baseline play characteristics from 1992 to 2017.*

Figure 5.7a. shows that women's *baseline points played* tended to increase over time, whereas *net points played* and *serve-volley points played* tended to decrease over time. However, *net points won* and *serve-volley points won* increased over time and *baseline points won* exhibited little change. The percentages of *net points played* and *serve-volley points played* were consistently lower than the percentage of *baseline points played*, whereas the percentage of *net points won* and *serve-volley points won* were consistently higher than the percentage of *baseline points won*.

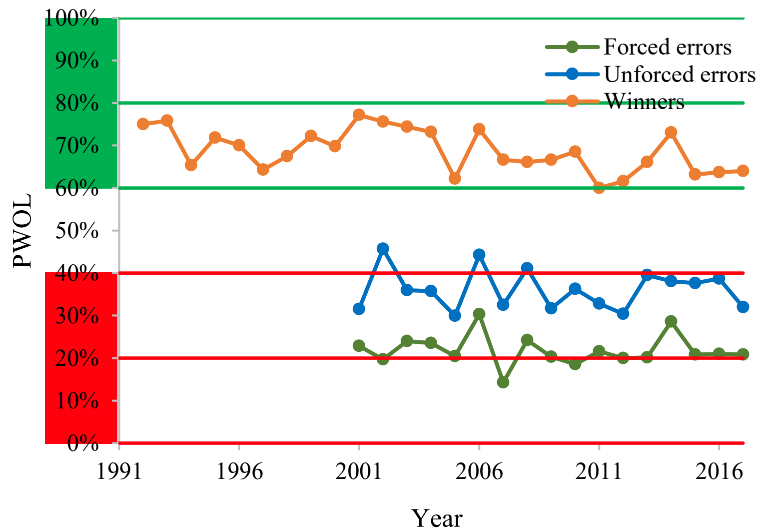
Figure 5.7b. shows that *baseline points won* was strongly associated with winning matches for women, with PWOL remaining above 80% throughout. With PWOL typically between 60% and 80%, *net points won* was associated with winning. *Baseline points played*, *net points played*, *serve-volley points played* and *serve-volley points won* tended not to be associated with match outcome, their PWOLs often between 40% and 60%.

Figures 5.8a. and 5.8b. display women's point-ending performance characteristics over time and associated PWOLs, respectively.

Figure 5.8.



a) *Women's mean point-ending characteristics from 1992 to 2017.*



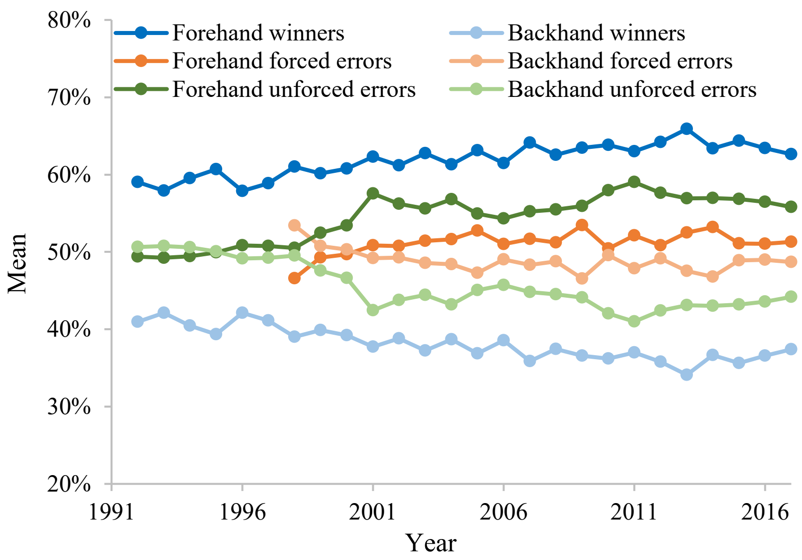
b) *PWOLs for women's point-ending characteristics from 1992 to 2017.*

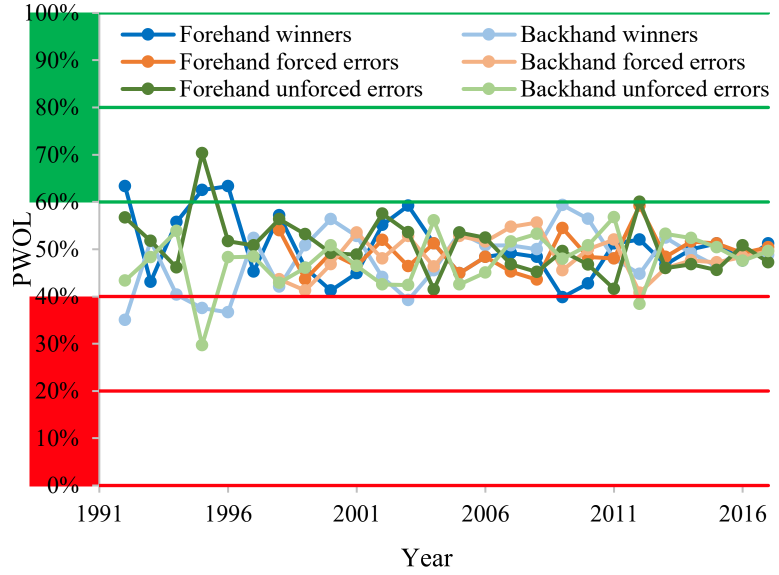
Figure 5.8a. shows that *forced errors* has been the most prevalent point-ending characteristic since their introduction in 2001. *Winners* gradually decreased from 36.0% in 1992 to 27.8% in 2001. *Unforced errors* increased from 22.2% in 2001 to 28.9% in 2005, whereas *forced errors* decreased from 50.0% in 2001 to 42.0% in 2005.

Figure 5.8b. shows that, with PWOL between 60% and 80% throughout, *winners* were associated with winning matches for women. *Unforced errors* were associated with losing matches, and PWOL for *forced errors* remained close to 20%, indicating a stronger association with match outcome than both *unforced errors* and *winners*.

Figures 5.9a. and 5.9b. display women's point-ending characteristics, stratified by groundstroke, over time and associated PWOLs, respectively.

Figure 5.9.





a) *Women's mean forehand and backhand point-ending characteristics from 1992 to 2017.*

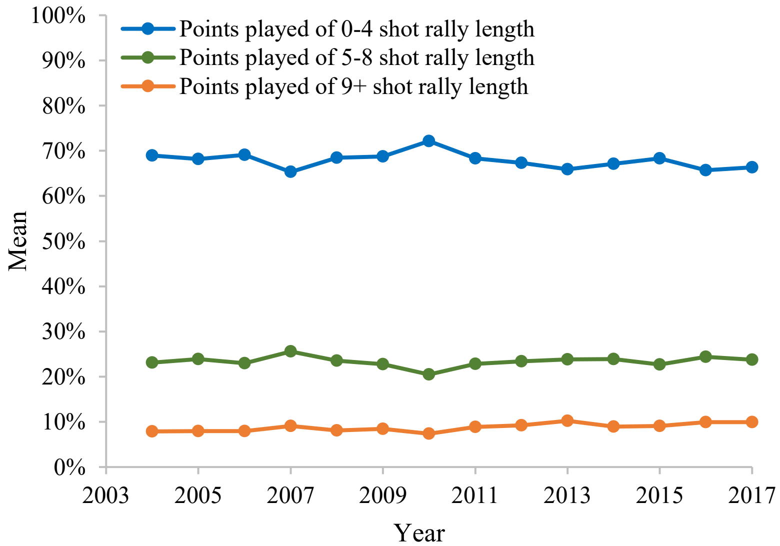
b) *PWOLs for women's forehand and backhand point-ending characteristics from 1992 to 2017.*

Figure 5.9a. shows that women's *forehand winners* increased between 1993 (57.9%) and 2013 (65.9%), and *forehand unforced errors* increased between 1993 (49.2%) and 2001 (58.5%). Prior to 1998, the percentages of *backhand unforced errors* and *forehand unforced errors* were similar, but from 1999 onwards, *forehand unforced errors* were more prevalent. *Forehand winners* were more prevalent than *backhand winners* throughout.

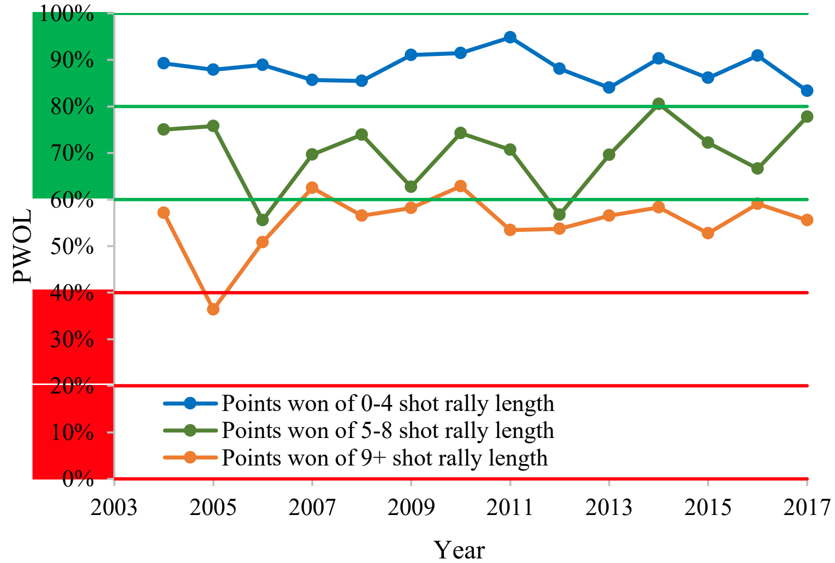
Figure 5.9b. shows that, for women, the six forehand and backhand point-ending performance characteristics were not typically associated with match outcome, with PWOLs between 40% and 60%, in almost all cases.

Figures 5.10a. and 5.10b. display women's percentage of points played of each rally length over time, and associated PWOLs, respectively.

Figure 5.10.



a) *Women's mean percentage of points played of each rally length from 2004 to 2017.*



b) *PWOLs for women's percentage of points won of each rally length from 2004 to 2017.*

Figure 5.10a. shows that, for women, *points played of 0-4 shot rally length* was consistently the most prevalent rally length, and *points played of 9+ shot rally length* was the least prevalent.

Figure 5.10b. shows that, of the three rally length categories, *points won of 0-4 shot rally length* was the most strongly associated with winning matches for women, as PWOL remained above 80% throughout, exceeding 90% five times between 2010 and 2016. *Points won of 5-8 shot rally length* was associated with winning matches, with PWOL between 60% and 80% in most cases, whereas *points won of 9+ shot rally length* typically exhibited no association with match outcome.

To summarise, the key findings were as follows:

- For players of both sexes, the four performance characteristics most strongly associated with winning matches were *points won of 0-4 shot rally length*, *first serve points won*, *first serve-return points won* and *baseline points won*.
- *Forced errors* and *unforced errors* were consistently associated with losing matches for both sexes.
- *Forehand winners* and *forehand unforced errors* have become more prevalent over time for both sexes, whereas *backhand winners* and *backhand unforced errors* have become less prevalent.
- Whether *winners*, *forced errors* and *unforced errors* originated from the forehand or backhand was not associated with match outcome.
- Baseline play has become more prevalent over time, whereas serve-volleying and other net-play have become less prevalent.
- *First serve speed* did not increase over time for either sex.
- Some performance characteristics have changed over time, but their associated PWOLs tended to remain within the same shaded zones.

5.3.3. Recent match-play summary

Table 5.3. displays men's and women's PWOLs for each performance characteristic for the most recent (available) three years of match-play (i.e. 2015-2017) combined.

Table 5.3. *PWOLs (and sample sizes) for men's and women's performance characteristics between 2015 and 2017.*

Performance characteristic	Men's PWOL	Women's PWOL
Points won of 0-4 shot rally length	93% (365)	87% (374)
First serve points won & first serve-return points won	86% (365)	85% (374)
Baseline points won	80% (365)	87% (374)
Second serve points won & second serve-return points won	75% (365)	78% (374)
Aces	69% (365)	62% (374)
Points won of 5-8 shot rally length	66% (365)	72% (374)
First serve speed	63% (218)	51% (210)
Net-points won	62% (365)	65% (374)
Winners	62% (365)	64% (374)
Successful first serves	59% (365)	56% (374)
Points won of 9+ shot rally length	59% (365)	56% (374)
Serve-volley points won	58% (217)	48% (42)
Backhand forced errors	55% (365)	48% (374)
Backhand unforced errors	51% (365)	49% (374)
Net points played	49% (365)	49% (374)
Serve-volley points played	49% (344)	56% (186)
Forehand winners	49% (365)	50% (374)
Backhand winners	49% (365)	48% (374)
Baseline points played	48% (365)	45% (374)
Forehand unforced errors	47% (365)	48% (374)
Forehand forced errors	44% (365)	50% (374)
Double faults	38% (365)	38% (374)
Unforced errors	35% (365)	36% (374)
Forced errors	26% (365)	21% (374)

Table 5.3. shows that, in recent years, *points won of 0-4 shot rally length* exhibited the highest PWOL for both sexes (joint highest for women) and was strongly associated with winning

matches. *First serve points won*, *first serve-return points won* and *baseline points won* were also strongly associated with winning matches, with PWOLs over 80%. *Forced errors* was the performance characteristic most strongly associated with losing matches for both sexes, with *unforced errors* and *double faults* also associated with losing. Twelve characteristics, including *points won of 9+ shot rally length*, *net points won*, *serve-volley points played,* and *serve-volley points won* demonstrated no association with match outcome in recent years, with PWOLs between 40% and 60%.

5.4. Discussion

The aim of this study was to establish the importance of each performance characteristic in terms of winning matches at Wimbledon. *Points won of 0-4 shot rally length, first serve points won*, *first serve-return points won* and *baseline points won* consistently exhibited the strongest associations with match outcome for men and women. With PWOL remaining above 80% in almost all cases, these four performance characteristics can be considered the most important in terms of winning matches, with superior performance in these areas closely associated with success. For players of both sexes, *forced errors* typically exhibited the lowest PWOLs, demonstrating a negative association with match outcome; thus, *forced errors* can be considered important, as they were associated with losing matches. *Unforced errors* also exhibited associations with losing. With PWOLs typically between 40% and 60%, several performance characteristics demonstrated no association with match outcome, including the six forehand and backhand point-ending characteristics, demonstrating that these may be considered less important.

5.4.1. Most important performance characteristics

For players of both sexes, *points won of 0-4 shot rally length* was the performance characteristic most strongly associated with winning matches. Men's and women's PWOLs for *points won* *of 0-4 shot rally length* often surpassed 90%, illustrating that players who won more points of 0-4 shot rally length (i.e. more short points) than their opponent won the match in over 90% of cases. As such, *points won of 0-4 shot rally length* are of great importance, as anecdotally reported by Anderson (2018a). Comparatively, *points won of 5-8 shot rally length* and *points won of 9+ shot rally length* were less important for both sexes. Research has consistently demonstrated that rally lengths are shorter on grass courts than other court surfaces (O'Donoghue & Ingram, 2001; Brown & O'Donoghue, 2008; Lane et al., 2017). Rally length data in the present study showed that points played of 0-4 shot rally length typically comprised over 70% of all points in men's matches (see Figure 5.5a.), and over 65% of all points in women's matches (see Figure 5.10a.). With such high proportions of all points played being of 0-4 shots, the considerable importance of short points on grass courts can be expected, and should not be underestimated by coaches and practitioners.

First serve points won and *first serve-return points won* were also strongly associated with winning matches. Previous research has highlighted the importance of serving in elite tennis (Hughes & Clarke, 1995; O'Donoghue & Ingram, 2001; Gillet et al., 2009), with Brown and O'Donoghue (2008) noting that the serve was more important on grass courts than any other surface. Evidence suggests that 60% of all points played at elite level are first serve points (O'Shannessy, 2019b). Data in the present study support these figures, with *successful first serve* percentages of approximately 62-63% for both sexes between 2015 and 2017 (i.e. 62-63% of all points were first serve points, see Figures 5.1a. and 5.6a). According to O'Donoghue and Brown (2008), the serve can be viewed as a perturbation, which affords the server an opportunity to destabilise the dynamic equilibrium of the point immediately, creating a tactical advantage. Pressure is then on the opponent to play an effective serve-return stroke that re-establishes the dynamic equilibrium. Crucially the effectiveness of a player's serve directly depends on the opponent's serve-return ability (Gillet et al., 2009), which exemplifies the importance of the serve-return. Gillet et al. (2009) noted that, as the serve is more difficult to return on faster court surfaces (such as grass), the serve and serve-return are even more crucial for creating opportunities to win the point. Additionally, Bollettieri (2015) suggested that points won within 3 shots can be directly attributable to the serve. So, with the prevalence and importance of short points already highlighted here, *first serve points won* and *first serve-return points won* are, understandably, highly important, and should be crucial components of grass court training sessions. It is worth noting too, that *second serve points won, second serve-return points won* and *aces* were also associated with winning matches, which further underlines the importance of the serve and serve-return in elite grass court tennis.

Baseline points won was the fourth performance characteristic to exhibit strong associations with winning matches for both sexes. Historically, grass courts have elicited less baseline play and more net play than hard and clay court surfaces (O'Donoghue & Ingram, 2001; Brown & O'Donoghue, 2008). More recently however, research has indicated that baseline play has become much more prevalent on all court surfaces, with players electing to remain close to the baseline, rather than approaching the net, which was a common tactic in the 1980s and 1990s (Crespo & Reid, 2007; Kor, 2017). This trend was evident here, with results revealing an increasing prevalence of baseline points over time, for men and women. It follows that, if a high proportion of points are now contested from the baseline, *baseline points won* would hold a degree of importance. In this way, the importance of *baseline points won* is likely a consequence of players approaching the net less often. Nevertheless, results demonstrate that effective baseline play is important at Wimbledon and this should therefore be reflected within elite players' grass court training sessions.

5.4.2. Other important performance characteristics

All three point-ending performance characteristics (*winners*, *forced errors* and *unforced errors*) were associated with match outcome. With PWOL consistently above 60% for both sexes, *winners* were associated with winning matches. Hence, being able to strategically 'build' a point (leading to a winner) and/or having aggressive groundstrokes, from which a player can produce winners, is important. From a dynamical systems perspective, a player can create a winner, or a perturbation that may lead to a winner, in three ways: by taking a calculated risk; by making an original or creative decision; or by imposing their own game-style and tempo of play on the opponent (Lebed, 2017). Each of these can disrupt the dynamic equilibrium during a point, leading to a player gaining a tactical advantage and potentially winning the point. One aspect of a coach's role is to determine which method may be most appropriate for their player to pursue during match-play.

In contrast, *forced errors* and *unforced errors* were associated with losing matches for both sexes, with PWOLs consistently below 40%. These results imply that players should aim to limit or reduce the number of *forced errors* and *unforced errors* they perform during a match, as this would increase their likelihood of winning. World-renowned tennis coach, Nick Bollettieri, professed that whichever player can make their opponent commit a forced error more often will usually win the match, and furthermore, that forcing opponent errors is central to any winning tennis strategy (Bollettieri, 2015). Although *forced errors* were not among the four most important performance characteristics here, results substantiate Bollettieri's observation, demonstrating that reducing forced errors is important in terms of winning matches at Wimbledon, particularly for women in recent years. *Forced errors* typically emerge as the result of an opponent's well-executed strategy (Striesend, 2013; Bollettieri, 2015), so it can be difficult for a coach to reduce the number of *forced errors* their player commits.

However, coaches may consider how to develop and adapt players' games, so they are better equipped to force errors from opponents more often.

5.4.3. Less important performance characteristics

Results showed that *forehand winners* and *forehand unforced errors* have become more prevalent over time for both sexes; correspondingly, *backhand winners* and *backhand unforced errors* have become less prevalent. These trends indicate an emergence of the forehand as the dominant groundstroke in elite men's and women's tennis, a finding that supports previous observations (Cam et al., 2013; Genevois et al., 2015; Kovalchik & Reid, 2018). PWOL analysis showed, however, that *forehand winners*, *forehand unforced errors, backhand winners* and *backhand unforced errors* were not associated with match outcome. So, whether a winner or unforced error originated from a player's forehand or backhand was not important. For example, hitting a higher proportion of forehand winners (compared to backhand winners) than the opponent, did not increase a player's likelihood of winning the match. Tennis rules dictate that a player wins a point if they hit a winner, and loses a point if they hit an unforced error, so, logically, how winners and unforced errors are performed is immaterial. Additionally, although most players prefer to attack using their forehand (Crespo & Higueras, 2001; Smith, 2004; Palmer, 2019), a player's weapons should be consistent with and reflective of their physical, technical and tactical abilities (Van Aken, 2002). So, despite the increasing prominence of the forehand stroke in elite match-play, it may be more prudent for coaches to develop whichever groundstroke a young player favours, as opposed to overemphasising forehand development and trying to ensure that the forehand becomes the dominant groundstroke or weapon.

5.4.4. Other notable findings

Previous research has shown that serve-volleying and other types of net-play have become less prevalent over time (Antoun, 2007; Kor, 2017). Results of the current study support this, with a decline in men's and women's *serve-volley points played* and *net-points played* evident for both sexes (see Figures 5.2a and 5.7a). Despite this, *serve-volley points won* and *net points won* consistently exhibited higher success rates than *baseline points won* (see Figures 5.2a and 5.7a). In this context, serve-volleying and approaching the net at other times during a point proved to be successful tactics, in comparison to baseline play. This finding is in line with O'Donoghue and Ingram's (2001) observation that players were more effective at the net than at the baseline. Despite this, players elected not to approach the net often.

From a tactical perspective, the decline in *serve-volley points played* and *net points played*, alongside their relatively high success rates could indicate that, in recent years, players have begun to approach the net only when they believe they have a strong tactical advantage during the point, and are therefore likely to win it. Supporting this theory, Antoun (2007) observed that female players often wait to see how effective their baseline stroke has been before deciding at the last moment whether to approach the net, and that, if their opponent appears to be in a defensive court position, the player may move forward in the hope of ending the point with an easy put-away volley. From a dynamical systems perspective then, players are tending to approach the net only after creating a perturbation that has destabilised the dynamic equilibrium of the point, such that the opponent is unlikely to perform effective defensive play that would smooth out the perturbation and re-establish the dynamic equilibrium; hence the perturbation is more likely to lead to a critical incident (i.e. the attacking player winning the point).

It has been commonly reported that first serve speeds have gradually increased over time (Crespo & Reid, 2007; Cross & Pollard, 2009; Foster, 2012), but this trend was not evident here. *First serve speed* was presented between 2004 and 2017, and with no serve speed data available here prior to 2004, it is difficult to ascertain precisely when the trend of gradually increasing first serve speeds ceased. Serve speed has been shown to be negatively correlated with the percentage of serves that are in (i.e. successful serves) (Gillet et al., 2009). In this way, the serve can be viewed as a trade-off between speed and accuracy. It is possible, therefore, that players have begun to focus more on the accurate placement of their first serves to gain a tactical advantage in the point, at the expense of further increasing their serve speed. The increase in *successful first serves* and simultaneous decrease in *double faults* over time, for both sexes in the present study, may support this theory, but further investigation (such as analysis of serve placement) would be needed to confirm.

Based on the results of this study, it is worth highlighting that a change in the mean value of a performance characteristic at Wimbledon did not necessarily translate into a change in that characteristic's association with match outcome (i.e. it's PWOL). For example, the prevalence of women's *baseline points played* increased by 24.5% between 1995 and 1996 (see Figure 5.7a.), but the performance characteristic was not associated with match outcome in either year (see Figure 5.7b.). Similarly, the prevalence of *forehand winners* and *forehand unforced errors* gradually increased for both sexes over time, but their level of importance did not change. So, even though research has demonstrated that the characteristics of elite tennis performance have changed over time (Brown & O'Donoghue, 2008; Takahashi et al., 2009), it should not be assumed that this inevitably translates into differences in the importance of those characteristics in terms of winning matches. It is therefore vital that coaches take into account performance characteristics' associations with match outcome, alongside trends or changes in the way the game is played when planning appropriate training designs and match-play strategies for players.

5.5. Conclusion

This chapter examined Wimbledon match-play between 1992 and 2017 to establish the importance of a range of performance characteristics, for men and women. *Points won of 0-4 shot rally length, first serve points won*, *first serve-return points won* and *baseline points won* were consistently the four performance characteristics most strongly associated with winning matches for both sexes. For this reason, they can be considered of great importance and should be central to grass court training sessions. *Forced errors* and *unforced errors* were associated with losing matches, so it is important for players to reduce the number of errors committed during match-play, to increase their likelihood of winning. Despite an increasing dominance of the forehand stroke, whether winners and errors emerged from the forehand or backhand was not linked to match outcome, so coaches should not necessarily encourage players to develop the forehand as a weapon, over the backhand. Finally, this chapter highlighted that, when analysing elite tennis match-play over time, it is crucial to consider, not only changes in the way the game is played, but also changes in how matches are won and lost (i.e. changes in each performance characteristic's association with match outcome) to ensure context.

Chapter 6

Identifying the most important performance characteristics at Wimbledon: close and one-sided matches

In this chapter, matches are classified as *closely contested* or *one-sided*, with operational definitions of these two terms derived from a combination of tennis coaches' expert knowledge, the researcher's expert knowledge and an explorative technique. Men's and women's Wimbledon match-play data recorded between 2015 and 2017 are examined using the PWOL method to identify the most important performance characteristics from the perspective of match closeness, to establish whether they differ in *closely contested* matches compared to *one-sided* matches.

6.1 Introduction

The performance characteristics of elite men's and women's tennis match-play at Wimbledon between 1992 and 2017 have been presented, and their importance in terms of winning matches discussed (Chapter 5). The most important performance characteristics for players of both sexes were *points won of 0-4 shot rally length, first serve points won, first serve-return points won,* and *baseline points won.* According to Csataljay et al. (2009), however, identifying the performance characteristics closely associated with success is most pertinent for sporting contests in which the difference between winning and losing players is small. In this context, research from sports including basketball (Gomez et al., 2008; Garcia et al., 2014), rugby union (Vaz et al., 2011), Gaelic football (Allister, et al., 2018) and handball (Oliveira et al., 2012) has suggested that the performance characteristics associated with success may differ in closely contested matches compared to one-sided matches. For example, Gomez et al. (2008) revealed that in closely contested basketball games (those with a final score difference between the two teams of 12 points or fewer), *defensive rebounds* best discriminated winning and losing teams, whereas in one-sided games (those with a final score difference of more than 12 points), *assists* best discriminated winning and losing teams. Based on these results, Gomez et al. (2008) were able to recommend greater specificity within training sessions around offensive strategies and the technical actions that lead to field-goal attempts.

In tennis, match closeness has primarily been considered from an economics perspective (e.g. Du Bois & Heyndels, 2007). Research in this area has suggested that the competitive balance of professional tennis matches (i.e. whether they are closely contested or one-sided) influences the level of public interest; generally, people prefer to watch matches with uncertain or less predictable outcomes (Du Bois & Heyndels, 2007). Evidence from team sport research proposes match closeness as a potentially useful stratification category in notational analysis studies, for several reasons. Investigating the influence of match closeness on the importance of performance characteristics in terms of winning matches can not only improve the specificity of training, but also inform match-play strategy (Hughes et al., 2017). If, for example, *double faults* were shown to discriminate winning and losing players in closely contested tennis matches, but not in one-sided matches, players may elect to change their serving strategy accordingly. Such investigations can also aid our understanding of sporting performance within different competitive contexts (Gomez et al., 2010). For example, tennis players often lose confidence in their second serve during closely contested matches, leading to anxiety and a decline in their performance level (Rutherford, 2017). If players understood that hitting a double fault was unlikely to affect their likelihood of winning the match, their loss in confidence may be ameliorated, their anxiety reduced, and their performance level maintained as a result. Furthermore, within their comprehensive investigation of hard court tennis match-play, Reid et al. (2016) recommended that future studies examine effects of match closeness on tennis match-play performance characteristics. As such, analysis from the perspective of match closeness may provide further insight into important performance characteristics in elite grass court tennis, better inform match-play strategies, and enhance the specificity and context of associated practical applications. To date, no published research has investigated the characteristics of tennis match-play from a match closeness perspective, so no operational definitions are available for *closely contested* and *one-sided* matches.

Therefore, the aims of this study were (i) to develop clear operational definitions for *closely contested* and *one-sided* tennis matches, and (ii) to establish whether the important performance characteristics in elite men's and women's grass court tennis differ by match closeness (i.e. between *closely contested* and *one-sided* matches).

6.2. Method

6.2.1. Matches

With institutional ethics approval, performance characteristics for men's and women's Wimbledon singles matches contested between 2015 and 2017 (men n = 381 and women n = 381) were obtained from the Wimbledon Information System (IBM, 2019). Access to the data was provided by IBM, with permission granted by The All England Lawn Tennis Club. Data from incomplete matches (i.e. those involving retirements, walkovers or defaults) were excluded; 16 men's matches and 7 women's matches were excluded and 365 men's matches and 374 women's matches remained in the sample.

6.2.2. Performance characteristics

The following were obtained for the winning and losing player in each match for a full list of definitions, see Appendix A):

- number of aces, number of double faults
- number of first serves attempted, number of first serves in
- number of serve-volley points played, number of serve-volley points won
- number of first serve points won, number of second serve points won
- number of first serve-return points won, number of second serve-return points won
- number of baseline points won, number of net points won
- number of forehand and backhand winners, number of forehand and backhand forced errors, number of forehand and backhand unforced errors
- total number of points played, total number of points won.
- number of points played and won of 0-4, 5-8 and 9+ shot rally length, respectively, and average (i.e. mean) first serve speed were obtained for matches where a serve speed radar was available.

Assessed using Cohen's kappa, the inter-rater reliability of the data was *k* = 0.99, defined as excellent (Fleiss, 1981; for full details of reliability testing, see Chapter 4).

6.2.3. Match closeness

No published research has provided operational definitions for *closely contested* and *one-sided* matches in tennis. Therefore, two Lawn Tennis Association (LTA) Level 5 Master Performance Coaches (n = 2, one female, one male) were given a Microsoft Excel (Microsoft Corp, Redmond, WA, USA) spreadsheet containing the final scores of all completed men's and women's Wimbledon matches contested between 2015 and 2017. All data were anonymised, and the order of matches randomised to reduce bias. Based on their *experiential knowledge* (i.e. knowledge gained from years of competing, developing and/or coaching in elite tennis; Woods et al., 2021), the coaches were asked to discuss the match scores and decide collectively whether each match was *closely contested* or *one-sided*. The researcher undertook the same process independently. The researcher's assessment agreed with the coaches' assessment in 95% of matches (705 of 739). The 34 matches whereby the researcher and the coaches disagreed on the classification were discussed and consensus on whether each was *closely contested* or *one-sided* was reached.

To determine objective operational definitions for *closely contested* and *one-sided* matches, an explorative technique was used alongside the coaches' and researcher's combined assessment. Different criteria (threshold values to optimise agreement) were tested for six statistics linked to match score (total number of points played in the match, total number of sets played in the match, mean number of games played per set, mean number of points played per set, percentage of games won by the losing player, and percentage of points won by the losing player), to identify which criterion demonstrated the strongest agreement with the coaches' and researcher's combined assessment. It became apparent that the criterion for *closely contested* and *one-sided* matches differed by sex. The process revealed that criteria based on the *percentage of games won by the losing player* demonstrated the strongest agreement with the coaches' and researcher's combined assessment for both sexes (see Table 6.1. for full details, ordered by sex and ascending level of agreement). Note that dual combinations of the six statistics were also tested, but all demonstrated lower agreement with the combined assessment than the criteria based on the *percentage of games won by the losing player*.

Table 6.1. *The number (and percentage) of matches whereby each tested criterion for* closely contested *matches agreed with the coaches' and researcher's combined assessment.*

Sex	*Closely contested* match criterion	Agreement with combined assessment
Men	Total number of sets > 3	281/365 (77.0%)
	Mean number of points per set > 57	287/365 (78.6%)
	Mean number of games per set > 9	297/365 (81.4%)
	Total number of points > 190	326/365 (89.3%)
	Percentage of points won by losing player > 44%	331/365 (90.7%)
	Percentage of games won by losing player > 38%	356/365 (97.5%)
Women	Total number of sets > 2	257/374 (68.7%)
	Mean number of points per set > 57	290/374 (77.5%)
	Mean number of games per set > 8.7	304/374 (81.3%)
	Percentage of points won by losing player > 43%	333/374 (89.0%)
	Total number of points > 120	334/374 (89.3%)
	Percentage of games won by losing player > 36%	358/374 (95.7%)

Agreeing with the combined assessment in 97.5% of men's matches (356 of 365) and 95.7% of women's matches (358 of 374), the criteria displayed in Table 6.2. were selected for this study.

Table 6.2. *Operational definitions for* one-sided *matches and* closely contested *matches for men and women.*

Sex	Operational definition	
	One-sided match	*Closely contested match*
Men	A match in which the losing player won ≤ 38.0% of games	A match in which the losing player won > 38.0% of games
Women	A match in which the losing player won ≤ 36.0% of games	A match in which the losing player won > 36.0% of games

Based on these operational definitions, each match in the dataset was stratified into one of two groups; *closely contested* matches or *one-sided* matches. Accordingly, 248 men's matches and 217 women's matches were classified as *closely contested*, with 117 men's matches and 157 women's matches classified as *one-sided*.

6.2.4. Data processing and analysis

Data were stratified by sex, year, match closeness (i.e. *closely contested* or *one-sided*) and match outcome (i.e. winning player or losing player), then normalised using the calculations presented in Table 6.3. before being reduced to mean values (± *sd*).

For each performance characteristic, the winning player's performance was compared to that of their opponent (i.e. the losing player), to establish which player outscored the other. Then, the *Percentage of matches in which the Winner Outscored the Loser* (PWOL) was calculated for each performance characteristic. PWOLs were used to indicate the relative importance of each characteristic in *closely contested* and *one-sided* matches, for male and female players respectively. PWOL interpretation is defined in Table 5.2. (Chapter 5).

To assess the agreement between the importance of each performance characteristic (i.e. their PWOLs) in *closely contested* matches and *one-sided* matches, a Spearman's rank-order correlation coefficient was calculated, for each sex.

Table 6.3. *Normalised performance characteristic calculations for Wimbledon, derived from O'Donoghue and Ingram (2001) and O'Donoghue (2005).*

Performance characteristic	Calculation
Aces (%)	Number of aces/number of serves performed x 100
Double faults (%)	Number of double faults/number of points served x 100
Successful first serves (%)	Number of first serves in/number of first serves attempted x 100
First serve points won (%)	Number of first serve points won/number of first serve points played x 100
First serve-return points won (%)	Number of first serve-return points won/number of first serve-return points played x 100
Second serve points won (%)	Number of second serve points won/number of second serve points played x 100
Second serve-return points won (%)	Number of second serve-return points won/number of second serve-return points played x 100
Serve-volley points played (%)	Number of serve-volley points played/number of serve points played x 100
Serve-volley points won (%)	Number of serve-volley points won/number of serve-volley points played x 100
Net points played (%)	Number of net points played/number of rally points played x 100
Net points won (%)	Number of net points won/number of net points played x 100
Baseline points played (%)	Number of baseline points played/number of rally points played x 100
Baseline points won (%)	Number of baseline points won/number of baseline points played x 100
Winners (%)	Number of winners/number of rally points played x 100
Forced errors (%)	Number of forced errors/number of rally points played x 100
Unforced errors (%)	Number of unforced errors/number of rally points played x 100
Forehand winners (%)*	Number of forehand winners/total number of groundstroke winners x 100
Backhand winners (%)*	Number of backhand winners/total number of groundstroke winners x 100
Points won of 0-4 shot rally length (%)	Number of points won of 0-4 rally length/number of points played of 0-4 rally length x 100
Points won of 5-8 shot rally length (%)	Number of points won of 5-8 rally length/number of points played of 5-8 rally length x 100
Points won of 9+ shot rally length (%)	Number of points won of 9+ rally length/number of points played of 9+ rally length x 100

* Calculations for forehand/backhand forced errors and forehand/backhand unforced errors replicate those for forehand/backhand winners.

6.3. Results

6.3.1. Men's results

Figure 6.1. displays PWOLs for all performance characteristics in men's *closely contested* and *one-sided* matches played between 2015 and 2017 at Wimbledon. Overall PWOLs for performance characteristics (i.e. PWOLs in *all* matches, as presented in Chapter 5, Table 5.3.) are also displayed, for context. Performance characteristics are displayed in descending order of PWOL for *all* matches (i.e. overall PWOLs; from left to right).

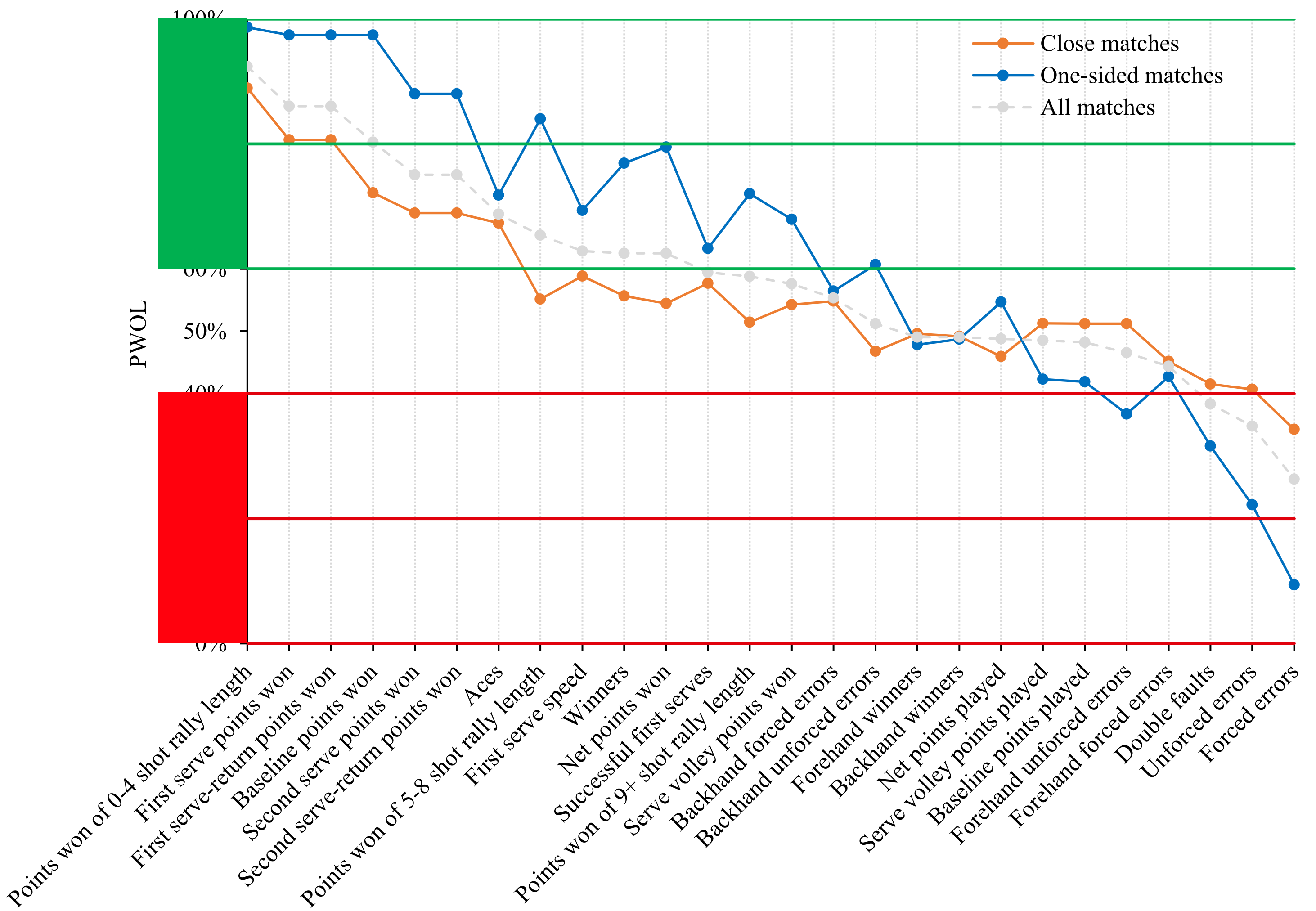


Figure 6.1. *Men's PWOLs for each performance characteristic, for* closely contested *matches,* one-sided *matches and* all *matches.*

Figure 6.1. shows that, for men, *points won of 0-4 shot rally length*, *first serve points won*, *first serve-return points won*, and *baseline points won* demonstrated the highest PWOLs in both *closely contested* and *one-sided* matches. Similarly, *forced errors*, *unforced errors* and *double faults* demonstrated the lowest PWOLs, irrespective of match closeness. Figure 6.1. also shows that *one-sided* matches typically elicited a PWOL further from 50% than *closely contested* matches, for any given performance characteristic. Additionally, the difference between PWOLs in *closely contested* and *one-sided* matches was generally smaller for characteristics with overall PWOLs (i.e. grey data points) closer to 50% and larger for those with overall PWOLs further from 50%. The difference between PWOLs in *closely contested* and *one-sided* matches was also smaller (relatively) for specific performance characteristics including *aces*, *first serve speed* and *successful first serves*, and larger for characteristics including *forced errors* and *points won of 5-8 shot rally length*.

Spearman's rank-order correlation coefficient, assessing the agreement between men's PWOLs for *closely contested* and *one-sided* matches, was calculated as $r_s = 0.89$ ($p < 0.001$), demonstrating excellent agreement (Hahs-Vaughn & Lomax, 2012).

6.3.2. Women's results

Figure 6.2. displays PWOLs for all performance characteristics in women's *closely contested* and *one-sided* matches, played between 2015 and 2017 at Wimbledon. Overall PWOLs for performance characteristics (i.e. PWOLs in *all* matches, as presented in Chapter 5, Table 5.3.) are also displayed, for context. Performance characteristics are displayed in descending order of PWOL for *all* matches (i.e. overall PWOLs; from left to right).

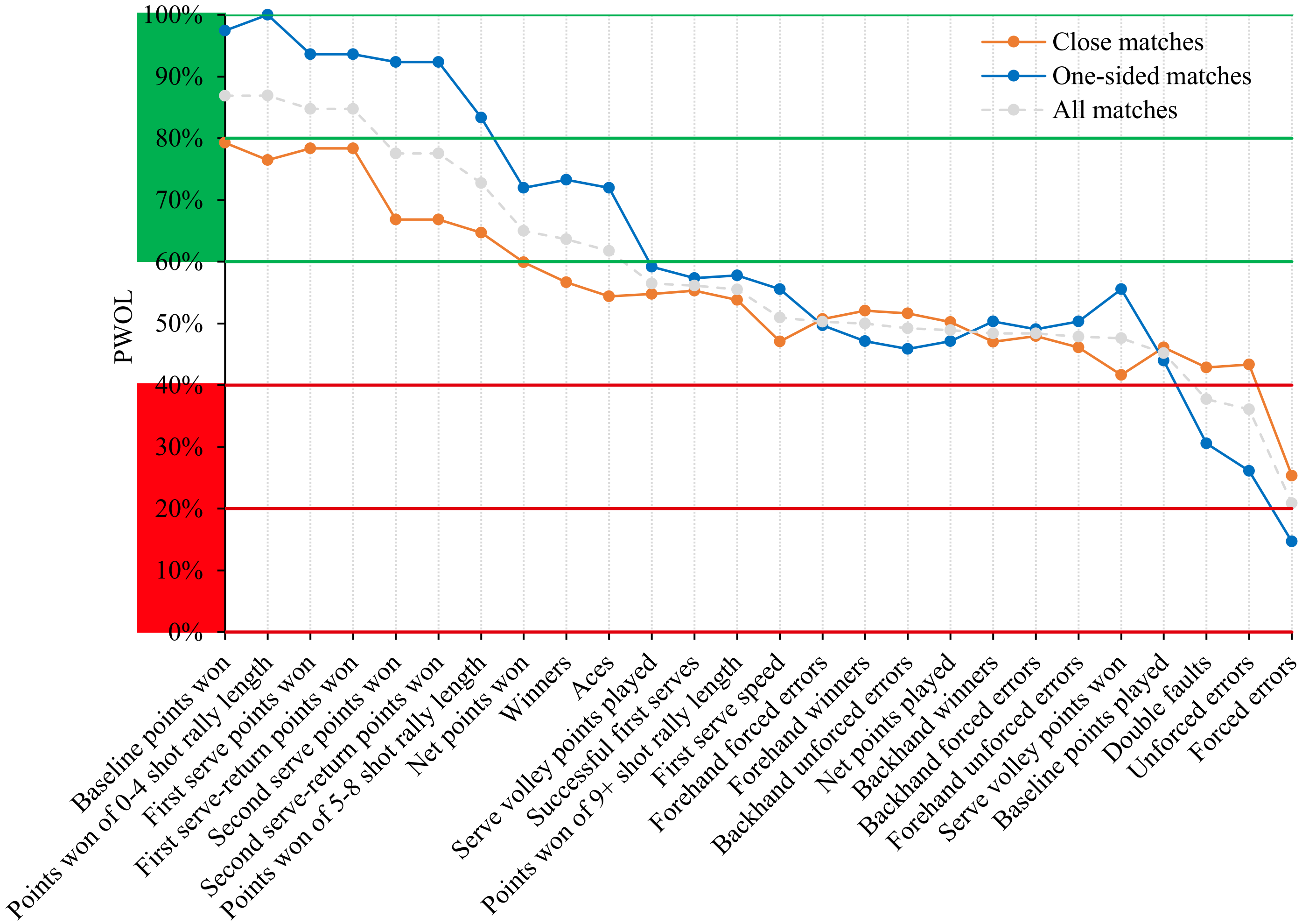


Figure 6.2. *Women's PWOLs for each performance characteristic, for* closely contested *matches,* one-sided *matches and* all *matches.*

Figure 6.2. shows that, for women, *baseline points won, points won of 0-4 shot rally length*, *first serve points won*, and *first serve-return points won* demonstrated the highest PWOLs in *closely contested* and *one-sided* matches. *Forced errors* and *unforced errors* demonstrated the lowest PWOLs, irrespective of match closeness. For women, as for men, *one-sided* matches typically elicited a PWOL further from 50% than *closely contested* matches, for any given performance characteristic. Also reflecting men's results, the difference between women's PWOLs in *closely contested* and *one-sided* matches tended to be smaller for those performance characteristics with overall PWOLs (i.e. grey data points) closer to 50% and larger for those with overall PWOLs further from 50%.

Spearman's rank-order correlation coefficient, assessing the agreement between women's PWOLs for *closely contested* and *one-sided* matches, was calculated as r_s =0.90 ($p < 0.001$), demonstrating excellent agreement (Hahs-Vaughn & Lomax, 2012).

6.4. Discussion

This study aimed to develop clear operational definitions for *closely contested* and *one-sided* tennis matches, and establish whether the important performance characteristics in elite men's and women's grass court tennis differ by match closeness. Based on the experiential knowledge of the researcher and two expert coaches, *closely contested* matches were defined as those in which the losing player won > 38% of games (for men), and > 36% of games (for women), whereas *one-sided* matches were defined as those in which the losing player won ≤ 38% of games (for men), and ≤ 36% of games (for women). No previous research had investigated tennis match-play from the perspective of match closeness, so it is proposed that the operational definitions developed here could be used in future to facilitate this type of analysis in different contexts (e.g. on other court surfaces).

Applying these operational definitions, analysis revealed that, for both sexes and irrespective of match closeness, the same performance characteristics exhibited the highest and lowest PWOLs, respectively. This observation was supported by Spearman's rank-order correlations, which demonstrated excellent agreement between the PWOLs in *closely contested* matches and those in *one-sided* matches. This shows that the order of importance of the performance characteristics (in terms of winning) was similar irrespective of match closeness; the performance characteristics that were the most (and least) important in *one-sided* matches were also the most (and least) important in *closely contested* matches. These results are in contrast to those from several team sport investigations, which suggested that the performance characteristics most closely associated with success differ in *closely contested* matches compared to *one-sided* matches (Gomez et al., 2008; Vaz et al., 2011; Oliveira et al., 2012; Garcia et al., 2014; Allister et al., 2018). Current results suggest therefore, that future research investigating important performance characteristics in grass court tennis need not stratify their data by match closeness (in turn decreasing the sample size and increasing confidence intervals) or account for any associated effect, and that expected match closeness (e.g. of an upcoming match) should not necessarily influence coaches' decision-making around the design of players' training sessions or strategy planning.

For players of both sexes, *points won of 0-4 shot rally length*, *first serve points won*, *first serve-return points won,* and *baseline points won* consistently exhibited the highest PWOLs, and are therefore the most important performance characteristics in elite grass court tennis, irrespective of match closeness. In men's and women's *one-sided* matches, PWOLs for these four characteristics were above 90%, indicating very strong associations with winning. In men's *closely contested* matches, *points won of 0-4 shot rally length*, *first serve points won* and *first serve-return points won* exhibited PWOLs above 80%, demonstrating strong associations with winning. This shows that these three characteristics differentiate between winning and losing players, even in *closely contested* matches. These findings highlight the critical nature of *points won of 0-4 shot rally length*, *first serve points won* and *first serve-return points won* at Wimbledon, and are particularly pertinent for coaches of male players, who should be aware that dominance in these areas can vastly improve players' chances of winning, irrespective of match closeness. This also strengthens the assertion made in Chapter 5, that the importance of short points in elite grass court tennis should not be underestimated; a notion supported by several tennis practitioners (e.g. Anderson, 2018a; Pretorius & Boucek, 2019; O'Shannessy, 2019a).

Although Spearman's correlations demonstrated excellent agreement between PWOLs in *closely contested* and *one-sided* matches, it should be noted that this agreement pertains only to the rank-order of the PWOLs, not the PWOLs themselves. For men and women, *one-sided* matches elicited PWOLs further from 50% than *closely contested* matches, for the majority of performance characteristics. This is evident in Figures 6.1. and 6.2., wherein the blue data points are higher than the orange data points for performance characteristics with overall (grey) PWOLs above 50% and lower than the orange data points for performance characteristics with overall PWOLs below 50%. Hence, the range in PWOLs was greater for *one-sided* matches than for *closely contested* matches. In terms of PWOL interpretation, this means that each performance characteristic's association with match outcome (whether positive or negative) was typically stronger in *one*-sided matches than in *closely contested* matches. Thus, the performance characteristics that were important in terms of winning in *closely contested* matches were even more important in *one-sided* matches. Given the nature of the scoring system in tennis, this can be expected. Several performance characteristics associated with winning matches (i.e. those with PWOLs above 60%) pertain to points won (e.g. *points won of 0-4 shot rally length*, *points won of 5-8 shot rally length*, *first serve points won*, *second serve points won*, *baseline points won*, *net points won*). The nature of the scoring system means that winning players intrinsically win considerably more points than losing players in *one-sided* matches (Wright et al., 2013), whereas this is not necessarily the case in *closely contested* matches. Therefore, the likelihood is that in *one-sided* matches, winning players will outperform losing players on any performance characteristics that pertain to points won more often than in *closely contested* matches; leading to the comparatively higher PWOLs in *one-sided* matches revealed here.

Interestingly, there appears to be more variation in the differences between the two sets of PWOLs (*closely contested* and *one-sided*) for men than for women. The greater amount of (visual) fluctuation in the results in Figure 6.1. (men) compared to those in Figure 6.2. (women) illustrates this. The fluctuation appears to be predominantly linked to the performance characteristics with overall PWOLs between 55% and 70%. Within this range, three serve-related characteristics – *first serve speed*, *successful first serves* and *aces* – demonstrated relatively smaller differences in PWOLs (i.e. importance) between *closely contested* and *one-sided* matches for men; contrastingly, characteristics including *forced errors* and *points won of 5-8 shot rally length* demonstrated relatively greater differences. This suggests that, irrespective of whether these characteristics were associated with match outcome, *first serve speed*, *successful first serves* and *aces* are not differentiating factors of match closeness (i.e. *closely contested* and *one-sided*) in elite men's tennis. In contrast, performance characteristics that exhibited greater differences in PWOLs between *closely contested* and *one-sided* matches, such as *forced errors* and *points won of 5-8 shot rally length*, do appear to differentiate between *closely contested* and *one-sided* men's matches. This may be because, of the three serve-related characteristics, *first serve speed* and *successful first serves* are not directly linked to winning a point (Whiteside & Reid, 2017), whereas *forced errors* and *points won of 5-8 shot rally length* are directly linked to winning a point. As mentioned, winning players are likely to outperform losing players more often in *one-sided* matches on performance characteristics pertaining to points won, as winning players win considerably more points overall than losing players. Conversely, *aces* are directly linked to winning a point, but they typically only comprise a small proportion of total points in a match (Whiteside & Reid, 2017), so they are less likely to have the same level of association with match closeness as *forced errors* and *points won of 5-8 shot rally length*, which each comprise a larger proportion of overall points played within a match. Another reason for the greater amount of fluctuation evident in the PWOLs for men's *one-sided* matches (compared to *closely contested* matches) could be the sample size of each group; 117 men's matches were categorised as *one-sided*, as opposed to 157 *one-sided* women's matches, and over 200 *closely contested* matches for both sexes, leading to comparatively higher confidence intervals for the PWOLs in men's *one-sided* matches.

6.5. Conclusion

This chapter first established operational definitions for *closely contested* and *one-sided* men's and women's tennis matches, which can be used in future studies, then investigated whether the important performance characteristics in elite grass court tennis differ by match closeness. Spearman's rank-order correlations demonstrated excellent agreement between PWOLs in *one-sided* matches and *closely contested* matches, indicating that the most (and least) important performance characteristics were similar in both types of matches for men and women. There is therefore no need for researchers to stratify performance data by match closeness in future investigations of elite grass court match-play, or for coaches to alter players' training sessions accordingly. This interpretation pertains only to the practical design of training sessions, however, rather than any psychological preparation that players might undertake prior to a potentially tough match (Hoskins, 2003; Bollettieri, 2015). Finally, although the *order* of importance of the performance characteristics was similar, it should be noted that the *level* of importance of several characteristics was greater in *one-sided* matches than in *closely contested* matches. Coaches should consider if and how this might guide players' match-play preparation.

Chapter 7

Important performance characteristics: investigating the court surface transition from clay to grass

This chapter presents match-play data from Roland Garros and Wimbledon, stratified by match outcome. The PWOL method is used to identify and compare the importance of a range of performance characteristics on two different court surfaces, clay and grass.

This chapter is based on the following peer-reviewed journal article: Fitzpatrick, A., Stone, J. A., Choppin, S. and Kelley, J. (2019b). Important performance characteristics in elite clay and grass court tennis match-play. *International Journal of Performance Analysis in Sport, 19*(6), 942-952.

7.1. Introduction

At present, tennis' four Grand Slams are each contested on a different outdoor court surface: the Australian Open on Plexicushion Prestige hard courts, Roland Garros on clay courts, Wimbledon on grass courts and the US Open on DecoTurf hard courts (International Tennis Federation, 2019). Court surfaces are characterised by two main properties: their coefficient of restitution and their coefficient of friction (Fernandez-Fernandez et al., 2009), and it is these two environmental constraints that help shape match-play on different surfaces. Elite tennis players are required to adapt to different court surfaces during the year, while attempting to maintain optimal performance levels. Therefore, understanding what constitutes success on different court surfaces would allow coaches to better prepare their players for competition (Over & O'Donoghue, 2008) and help to ensure smooth, efficient transitions between surfaces.

Previous studies have demonstrated that the differences in match-play characteristics (e.g. rally length, percentage of first serve points won, number of net-points played), between Roland Garros and Wimbledon are greater than between all other pairs of Grand Slams (Takahashi et al., 2006; Brown & O'Donoghue, 2008; Cui et al., 2018). Furthermore, with only 3 weeks typically separating Roland Garros and Wimbledon, players must adapt their training strategies and attempt to reach optimal performance levels in a short time frame, so the surface transition from clay to grass is arguably the most important to understand. Despite this, it is not currently known whether the match-play characteristics that are most important in terms of winning matches on these two surfaces differ. Establishing this would enable better informed training for players during this critical surface-change period. It would also support the periodisation of training, whereby sub-seasons (e.g. the clay court season, the grass court season) are characterised by surface-specific training methods (Over

& O'Donoghue, 2008; Reid et al. 2016). Therefore, the aim of this study was to identify important match-play characteristics on clay and grass court surfaces, for elite male and female tennis players.

7.2. Method

7.2.1. Matches

With institutional ethics approval, performance characteristics for the 2016 and 2017 Roland Garros (men n = 244, women n = 250) and Wimbledon (men n = 241, women n = 249) singles matches were obtained from the Roland Garros (2017) website and the Wimbledon Information System (IBM, 2019). Permission to use the Roland Garros data was granted by the Fédération Française de Tennis, and access to the Wimbledon data was provided by IBM, with permission granted by The All England Lawn Tennis Club. Data from incomplete matches (i.e. those involving retirements, walkovers or defaults) were excluded from the study; 23 men's matches and 9 women's matches were excluded accordingly.

7.2.2. Performance characteristics

The following performance characteristics were obtained for winning and losing players in each match (for a full list of definitions, see Appendix A):

- number of aces, number of double faults
- number of first serves in
- average (i.e. mean) first serve speed*
- number of first serve points won, number of second serve points won
- number of first serve-return points won, number of second serve-return points won
- number of baseline points won, number of net points won
- number of break points won
- number of winners, number of forced errors, number of unforced errors
- number of points won of 0-4, 5-8 and 9+ shot rally length+, respectively*.

[*] Collected only for those matches where a serve speed radar was available.

Note that this list of performance characteristics is not as comprehensive as those in Chapters 5 and 6, as the data presented on the Roland Garros website were limited in comparison to those available via the Wimbledon Information System.

7.2.3. Reliability testing

The organisation committee for each Grand Slam is responsible for recruiting and training their own data entry teams. As such, different teams were present at each event, so the reliability of the data from each Grand Slam had to be evaluated separately. To enable inter-rater reliability testing between the researcher and the data entry teams at each event, video recordings of eight matches (two men's matches and two women's matches per Grand Slam) were observed and coded independently by the researcher, using a NacSport (NacSport Elite, Las Palmas de Gran Canaria, Spain) custom-notational analysis system. Cohen's kappa coefficient was calculated, based on analysis of over 200 match-play points per Grand Slam, comparing the researcher's results with those recorded by the Grand Slams' respective data entry teams. Cohen's kappa coefficient was $k = 0.97$ for the Roland Garros data and $k = 0.99$ for the Wimbledon data, identified as excellent (Fleiss, 1981).

7.2.4. Data processing and analysis

Data were reduced to mean (± *sd*) for male and female winning and losing players, respectively. For each performance characteristic, the winning player's performance was compared to that of their opponent, to establish which player outscored the other; then, the *Percentage of matches in which the Winner Outscored the Loser* (PWOL) was calculated. To assess the agreement between the importance of each performance characteristic (i.e.

their PWOLs) at Roland Garros and Wimbledon, a Pearson's correlation coefficient was calculated, for each sex (after the data had satisfied the assumptions of parametricity).

To aid interpretation of results, the mean percentage of points played (per match) within each rally length category was also calculated for both sexes on clay and grass. Mann-Whitney *U*-tests were used to identify court surface differences in the mean percentage of points played within each rally length category for men and women, respectively.

7.3. Results

Table 7.1. displays the mean values for each performance characteristic, for winning and losing male players at Roland Garros and Wimbledon, and associated PWOLs.

Table 7.1. *Mean (± sd) for each performance characteristic for winning and losing male players at Roland Garros and Wimbledon, and associated PWOLs.*

Performance characteristic	Roland Garros			Wimbledon		
	Winning players	Losing players	PWOL	Winning players	Losing players	PWOL
Number of points won of 0-4 shot rally length	83.1 ± 23.6	70.2 ± 25.8	89%	81.8 ± 25.4	67.9 ± 28.5	92%
Number of first serve points won	48.9 ± 14.7	44.3 ± 15.6	85%	56.4 ± 17.0	50.8 ± 18.3	85%
Number of baseline points won	69.6 ± 20.0	56.7 ± 22.3	82%	55.2 ± 18.0	45.3 ± 18.7	79%
Number of second serve points won	22.8 ± 7.4	20.6 ± 8.2	77%	22.5 ± 7.5	21.7 ± 8.0	73%
Number of break points won	5.5 ± 2.0	2.5 ± 2.1	71%	4.5 ± 1.7	1.7 ± 1.6	68%
Number of points won of 9+ shot rally length	12.3 ± 7.6	10.3 ± 7.3	66%	8.7 ± 6.1	7.0 ± 5.8	61%
Number of points won of 5-8 shot rally length	23.2 ± 8.2	20.1 ± 8.9	65%	22.4 ± 8.4	18.9 ± 8.2	69%
Number of winners	39.0 ± 13.7	33.6 ± 14.5	64%	29.2 ± 10.6	25.0 ± 11.1	61%
Number of net points won	14.1 ± 8.0	13.8 ± 8.4	62%	21.2 ± 9.8	19.8 ± 11.0	57%
Number of aces	7.5 ± 6.4	5.7 ± 4.7	59%	12.5 ± 8.5	9.1 ± 7.9	68%
Number of successful first serves	66.2 ± 21.3	67.6 ± 21.3	56%	72.0 ± 22.3	73.0 ± 21.7	61%
Average first serve speed (km/h)	181.8 ± 9.7	180.9 ± 10.7	51%	188.6 ± 8.8	185.2 ± 10.2	60%
Number of double faults	3.4 ± 2.5	3.8 ± 2.7	44%	3.4 ± 2.5	4.5 ± 2.6	33%
Number of unforced errors	30.9 ± 14.9	37.4 ± 14.8	33%	21.9 ± 10.5	25.7 ± 10.6	33%
Number of forced errors	36.2 ± 13.2	42.2 ± 12.8	22%	44.5 ± 14.8	50.0 ± 13.4	27%

Table 7.1. shows that for male players on clay and grass, the four performance characteristics with the highest PWOLs were *points won of 0-4 shot rally length*, *first serve points won*, *baseline points won* and *second serve points won*. *Forced errors* and *unforced errors* demonstrated the lowest PWOLs on both surfaces. *Aces*, *double faults*, *successful first serves* and *average first serve speed* exhibited PWOLs between 40% and 60% at Roland Garros, but outside of this range at Wimbledon.

Pearson's correlation coefficient, assessing the agreement between men's PWOLs for Roland Garros and Wimbledon, was calculated as $r = 0.95$ ($p < 0.001$), demonstrating excellent agreement (Hahs-Vaughn & Lomax, 2012).

Table 7.2. displays the mean values for each performance characteristic, for winning and losing female players at Roland Garros and Wimbledon, and associated PWOLs.

Table 7.2. *Mean (± sd) for each performance characteristic for winning and losing female players at Roland Garros and Wimbledon, and associated PWOLs.*

Performance characteristic	Roland Garros			Wimbledon		
	Winning players	Losing players	PWOL	Winning players	Losing players	PWOL
Number of points won of 0-4 shot rally length	52.8 ± 15.8	43.7 ± 17.3	85%	48.4 ± 14.2	39.0 ± 16.3	87%
Number of baseline points won	49.8 ± 14.4	40.4 ± 16.0	84%	44.0 ± 13.2	35.6 ± 15.7	90%
Number of first serve points won	30.5 ± 9.3	25.8 ± 10.1	83%	32.0 ± 9.9	28.0 ± 11.3	84%
Number of second serve points won	12.5 ± 4.9	11.0 ± 5.4	76%	13.3 ± 5.0	11.5 ± 5.3	79%
Number of winners	25.3 ± 9.5	20.6 ± 11.3	68%	20.3 ± 9.0	16.6 ± 8.9	64%
Number of points won of 5-8 shot rally length	17.1 ± 7.2	14.8 ± 7.6	68%	17.9 ± 7.2	14.5 ± 7.1	72%
Number of break points won	5.1 ± 1.7	2.8 ± 1.9	66%	4.5 ± 1.4	2.1 ± 1.7	63%
Number of successful first serves	46.3 ± 15.6	45.4 ± 14.6	58%	45.5 ± 16.3	45.8 ± 15.9	57%
Number of aces	2.5 ± 2.4	1.8 ± 2.2	57%	3.4 ± 3.0	2.5 ± 2.6	57%
Number of points won of 9+ shot rally length	8.7 ± 5.7	7.6 ± 5.6	56%	7.4 ± 5.5	6.2 ± 4.9	58%
Number of net points won	8.2 ± 5.0	7.8 ± 5.9	54%	10.9 ± 6.8	9.0 ± 5.6	66%
Average first serve speed (km/h)	155.3 ± 10.5	154.7 ± 9.9	52%	159.4 ± 9.5	158.4 ± 8.4	51%
Number of double faults	2.8 ± 2.4	3.1 ± 2.3	46%	2.8 ± 2.2	3.6 ± 2.3	35%
Number of unforced errors	22.8 ± 10.2	27.7 ± 11.0	34%	17.0 ± 9.3	20.5 ± 9.7	35%
Number of forced errors	21.9 ± 9.3	25.4 ± 9.0	34%	25.5 ± 10.3	30.7 ± 10.0	21%

Table 7.2. shows that for female players, *points won of 0-4 shot rally length*, *baseline points won, first serve points won* and *second serve points won* had the highest PWOLs on clay and grass. *Forced errors* and *unforced errors* exhibited the lowest PWOLs on both surfaces. The serving characteristics (*aces*, *double faults*, *successful first serves* and *average first serve speed*) all exhibited PWOLs between 40% and 60% at Roland Garros, and of these, only *double faults* demonstrated a PWOL outside of this range (35%) at Wimbledon.

Pearson's correlation coefficient, assessing the agreement between women's PWOLs for Roland Garros and Wimbledon, was calculated as $r = 0.96$ ($p < 0.001$), demonstrating excellent agreement (Hahs-Vaughn & Lomax, 2012).

Table 7.3. displays the mean percentage of points (per match) played within each rally length category for men and women on clay (Roland Garros) and grass courts (Wimbledon).

Table 7.3. *Mean percentage of points played within each rally length category for men and women at Roland Garros and Wimbledon.*

Rally length	Men		Women	
	Roland Garros	Wimbledon	Roland Garros	Wimbledon
0-4 shot rally length	69.0%	72.1%*	65.1%	65.9%
5-8 shot rally length	20.2%	20.1%	23.4%	24.1%
9+ shot rally length	10.8%	7.8%*	11.5%	10.0%$^{+}$

* Different to men at Roland Garros ($p < 0.001$).

$^{+}$ Different to women at Roland Garros ($p < 0.05$).

Table 7.3. shows that, for men, the mean percentage of points of 0-4 shot rally length was 3.1% higher at Wimbledon than Roland Garros, whereas the mean percentage of points of 9+ shot rally length was 3.0% lower at Wimbledon. For women, the mean percentage of points of 9+ shot rally length was 1.5% lower at Wimbledon than Roland Garros.

7.4. Discussion

The aim of this study was to identify important match-play characteristics on clay and grass court surfaces, for both sexes. Analysis showed that the same performance characteristics exhibited the highest and lowest PWOLs, respectively, on both court surfaces. This observation was supported by Pearson's rank-order correlations, which demonstrated excellent agreement between the PWOLs at Roland Garros and Wimbledon, for men and women. *Points won of 0-4 shot rally length*, *first serve points won*, *baseline points won* and *second serve points won* exhibited the highest PWOLs (i.e. were most closely associated with success) for players of both sexes, at Roland Garros and Wimbledon; hence, these four performance characteristics are important in terms of winning matches on clay and grass courts. *Forced errors* and *unforced errors* exhibited the lowest PWOLs for both sexes, demonstrating that these are also important as they were associated with losing matches on both surfaces. Often demonstrating PWOLs between 40% and 60%, serve-related performance characteristics are considered less important, however several serve-related characteristics were more important on grass than on clay, particularly for male players. While previous research has suggested that match-play characteristics differ depending on court surface, results here show that these differences do not necessarily translate to differences in the *importance* of each characteristic.

7.4.1. Performance characteristics associated with winning

For both sexes, *points won of 0-4 shot rally length*, *first serve points won*, *baseline points won* and *second serve points won* were the most closely associated with winning on clay and grass courts. However, approximately 60% of points in elite tennis are 'first serve points' and 40% of points are 'second serve points' (O'Shannessy, 2019b), so it is understandable that both *first serve points won* and *second serve points won* are important. It is also well documented that baseline play has dominated the game since the turn of the century, in contrast to the 1980s and

1990s, when net play was more prevalent (Crespo & Reid, 2007). For this reason, the importance of *baseline points won* is understandable. Additionally, all four of these performance characteristics pertain to 'points won', so it follows that they are likely to be somewhat associated with winning matches.

Despite each pertaining to 'points won', of the three rally length performance characteristics, *points won of 0-4 shot rally length* (i.e. short points) was considerably more important than *points won of 5-8 shot rally length* (i.e. medium length points) and *points won of 9+ shot rally length* (i.e. long points), irrespective of court surface and sex. Grass courts have often been shown to exhibit the shortest rally lengths compared to other court surfaces (O'Donoghue & Ingram, 2001; Brown & O'Donoghue, 2008), so high PWOLs might be expected for *points won of 0-4 shot rally length* on grass courts. However, the importance of winning short points at Roland Garros was not expected, as rally lengths and durations have consistently been shown to be longest on clay courts (O'Donoghue & Ingram, 2001; Takahashi et al., 2006; Martin et al., 2011); although since the mid-2000s, the differences between rally lengths on different surfaces have reduced somewhat (Brown & O'Donoghue, 2008; Martin & Prioux, 2016; Lane et al., 2017). In this analysis, male players who won more short points than their opponent won the match in 89% of cases at Roland Garros. Despite clay courts typically being associated with long rallies, the data presented in Table 7.3. reveals an underlying prevalence of short points on both surfaces. While perhaps unexpected, this helps explain why short points are so important on clay, as well as on grass, as they comprised a large proportion of total points played on both surfaces. In turn, this also indicates that the outcome of a large proportion of points may be determined by the quality of the serve and/or the serve-return.

In a coaching context, the importance of short points and their prevalence on the two surfaces are relevant. Pinder et al. (2011) explained that to optimise learning, athletes' training sessions should be representative of the performance environment (i.e. match-play). Therefore, results here suggest that elite players' practice sessions should not have an over-emphasis on long rallies and consistency during the clay and grass court seasons, but should instead afford sufficient time to practising serves, serve-returns and point-ending strategies, to be representative of match-play. Importantly, future work to identify how points of 0-4 shot rally length are won would be beneficial and provide further insight here, particularly as this performance characteristic exhibited the highest PWOL in 3 of the 4 instances.

7.4.2. Performance characteristics associated with losing

For both sexes, *forced errors and unforced errors* were the performance characteristics most closely associated with losing on clay and grass. For male players, *forced errors* exhibited a lower PWOL (closer to 0%) than *unforced errors* at Roland Garros and Wimbledon, suggesting that *forced errors* are more important than *unforced errors* for men on both surfaces. This can be explained in the context of gamestyles. Tactically, male players typically attempt to exploit free space on the court, using different spins and ball speeds to put opponents under pressure, which is safer than implementing a 'power' gamestyle (Antoun, 2007), and is therefore likely to induce more *forced errors* than *unforced errors*. In contrast, female players, who are typically not as strong and demonstrate less tactical variety than men, tend to adopt riskier power-hitting gamestyles (Rutherford, 2017), striking the ball earlier and flatter in an attempt to apply pressure and out-hit opponents (Antoun, 2007); a tactic that presents an inherent risk of 'over-hitting' (i.e. committing an unforced error). For this reason, it could be expected that *unforced errors* would be more important than *forced errors* for women, but this was not the case. *Forced errors* were more important than *unforced errors* for women at Wimbledon and the two exhibited equal importance at Roland Garros. This could indicate a change in gamestyles for women in recent years; perhaps they have begun to implement more tactical variety, rather than solely power-hitting. However, given the subjectivity involved when classifying errors as ‘forced’ or ‘unforced’, differences in the data collection practices at the two Grand Slams cannot be ruled out, so these results must be interpreted with caution. Either way, it is important for coaches to be aware of and understand the differences in tennis strategies between men and women, so any expectations and goals set are realistic and sex-specific.

7.4.3. Performance characteristics least associated with match outcome

For male players, four serve-related performance characteristics (*aces*, *successful first serves*, *double faults* and *average first serve speed*) exhibited PWOLs between 40% and 60% on clay (indicating that serving is not important in terms of winning), but outside of this range on grass (*double faults* - 33%, *average first serve speed* - 60%, *successful first serves* - 61%, *aces* - 68%). This suggests men’s serving is more important on grass than on clay. This also corresponds with the differences in rally lengths between the two events (see Table 7.3.); the fact that more short points were played by men at Wimbledon than at Roland Garros may be a reflection of the greater importance of the serve on grass than on clay. On grass courts, the lower coefficients of friction and restitution (compared to clay) mean that, after a serve lands, the ball loses less horizontal velocity and bounces lower (Miller, 2006). Accordingly, the ball approaches the returning player faster, affording them less time to prepare for and perform the serve-return (Filipcic et al., 2011). The returner is therefore less likely to successfully return the serve into play, so the server might win a higher proportion of points directly from their serve. If players recognise this, intuitively or otherwise, it could also explain the higher serve speeds at Wimbledon, where a fast serve may be more likely to be rewarded with a ‘cheap’ point than on the slower, higher bouncing clay courts at Roland Garros (Giampaolo & Levey, 2013).

For female players, *aces*, *successful first serves* and *average first serve speed* exhibited PWOLs between 40% and 60% on both court surfaces, with only *double faults* exhibiting a PWOL outside of that range (35%) at Wimbledon. So, it appears that serving is not important in terms of winning matches on clay or grass for women. This supports previous observations that the serve is a more effective weapon for male players than female players (Furlong, 1995), and that tactically, women tend to use their serves as a means of starting a point, rather than gaining an advantage or winning points directly (Filipcic et al., 2011). With female players typically producing lower serve speeds than male players, returners are afforded more time to plan and perform the serve-return, so points are less likely to be won directly from the serve.

In a practical context, these serve-related results indicate that enhancing a player's serve performance should not be a priority for coaches during the clay court season, and that only male players should afford serving additional practice time during the grass court season. Interestingly, though, *first serve points won* and *second serve points won* exhibited relatively high PWOLs (73%+) for men and women on both court surfaces. So, perhaps the serve allows players to gain somewhat of a 'lasting' advantage in the rally, even though the more 'immediate' serving characteristics (*aces, double faults, first serve percentage* and *average first serve speed*) do not appear to be of great importance, particularly on clay. If this is the case, it may be prudent for coaches to focus on integrating the serve into a player's holistic match-play strategy rather than aiming to win points directly from their serve.

7.5. Conclusion

Demonstrating excellent agreement between PWOLs at Roland Garros and Wimbledon, *points won of 0-4 shot rally length*, *first serve points won*, *baseline points won* and *second serve points won* were most closely associated with winning for players of both sexes, on clay and grass court surfaces. Accordingly, short points and point-ending strategies should be a focus for players during grass and clay court season training. *Forced errors* and *unforced errors* were most closely associated with losing on both surfaces, and serve-related characteristics were somewhat important for male players on grass. Pertinently for coaches, these results suggest that training need not drastically differ for either sex when transitioning from clay courts to grass courts, but that male players may wish to afford extra practice time to serving during the grass court season. Accordingly, players might wish to prioritise getting used to the court surface (e.g. modifying their movement patterns and adapting to the different ball-court surface interactions), rather than specific areas of their game, such as approach shots or net-play, when transitioning from clay to grass in preparation for Wimbledon. Additionally, future work analysing short points in more detail would enhance our understanding around their importance, revealing how such points are won by elite male and female players.

Chapter 8

Investigating the most important performance characteristic at Wimbledon: points won of 0-4 shot rally length

Informed by the studies presented in Chapters 5, 6 and 7, this chapter investigates the most important performance characteristic in elite grass court tennis, *points won of 0-4 shot rally length*, in more detail. Individual rally lengths (i.e. points of 0 shots, 1 shot, 2 shots, 3 shots and 4 shots, respectively) are analysed to establish their prevalence and importance in terms of winning matches at Wimbledon. Note that the term ‘short points’ is often used in place of ‘points of 0-4 shot rally length’ in this chapter, for conciseness.

This chapter is based on the following peer-reviewed journal article: Fitzpatrick, A., Stone, J. A., Choppin, S. and Kelley, J. (2021). Investigating the most important aspect of elite grass court tennis: short points. *International Journal of Sports Science & Coaching,* https://doi.org/10.1177/1747954121999593

8.1. Introduction

Chapters 5, 6 and 7 applied the newly validated PWOL method to identify important performance characteristics in terms of winning elite men's and women's tennis matches at Wimbledon. Results showed that *points won of 0-4 shot rally length* (i.e. short points) was the most important characteristic, with players who won more short points than their opponent typically winning the match in over 80% of cases, irrespective of sex, time (Chapter 5), match closeness (Chapter 6) and court surface (Chapter 7). Analysis also revealed an underlying prevalence of short points on grass courts for players of both sexes. With 65.9% (for women) and 72.1% (for men) of all points played at Wimbledon between 2015 and 2017 ending in fewer than 5 shots (see Table 7.3.), short points should be a key area of interest for coaches. Results so far support the subjective opinions of several tennis practitioners, who have suggested that the first four strokes of each rally are crucial in elite tennis match-play (Annacone, 2018; Pretorius & Boucek, 2019; O'Shannessy, 2019a). To the researcher's knowledge, no published research has investigated short points specifically; for example, breaking down the 0-4 shot rally length category and analysing each individual rally length (i.e. 0 shots, 1 shot, 2 shots, 3 shots and 4 shots, respectively), to reveal more detailed insights.

Stratifying the 0-4 shot rally length category into individual rally lengths could reveal aspects such as the single most common rally length (i.e. 0, 1, 2, 3 or 4 shots) and the most important rally length in terms of winning matches (i.e. the rally length that winning players dominate to the greatest extent). Additionally, researchers and expert tennis practitioners have described the serve and serve-return as the two most important strokes in tennis (e.g. Gillet et al., 2009; Klaus et al., 2017; Ruder, 2019; O'Shannessy, 2019a), but limited empirical research has sought to objectively investigate their importance. Stratifying short points in this way could provide clearer insight into the importance of the serve and serve-return in elite tennis.

Therefore, this study investigates men's and women's *points won of 0-4 shot rally length* (i.e. short points). The aim was to identify the prevalence of each individual rally length and the importance of each rally length for men and women, in terms of winning matches at Wimbledon.

8.2. Method

8.2.1. Matches

With institutional ethics approval, point-level data from men's and women's Wimbledon singles matches played between 2015 and 2017 (men n = 211, women n = 209) were obtained from the Wimbledon Information System (IBM, 2019). This time frame was selected, firstly, because prior to 2015, point-level data were only available for a smaller and therefore less representative sample of matches, due to technological limitations. Secondly, data from these years were the most contemporary available, and are therefore more pertinent to current coaches and practitioners (Carling et al., 2005). Finally, data from 2015 to 2017 were available within all grass court datasets analysed in this thesis (i.e. those in Chapters 5, 6, 7 and 9), so the matches in each sample were consistent, where possible.

Access to the data was provided by IBM, with permission granted by The All England Lawn Tennis Club. The following were obtained for all points in each available match:

- match ID
- point winner
- match winner
- rally length (i.e. the exact number of strokes per point).

Note that the rally length of a point was comprised only of successful strokes (i.e. strokes whereby the ball crossed the net, to the side of the opponent, and landed inside the court); errors were not counted. For example, a point of *0 shots* would be a double fault, and a point of *1 shot* would either be an ace or a missed serve-return. Data were available only for matches where a serve speed radar was in use. Data from matches involving retirements, walkovers or defaults (8 men's matches and 3 women's matches) were excluded from the study.

8.2.2. Data processing and analysis

Using Microsoft Excel (Microsoft Corp, Redmond, WA, USA), the data were stratified by sex and filtered to exclude all points with a rally length of greater than 4 shots. Points were then stratified into 5 individual rally lengths (i.e. points played of 0 shots, 1 shot, 2 shots, 3 shots and 4 shots, respectively). To establish the prevalence of each rally length for each sex, the number of points played of each individual rally length was summed at match level. Using SPSS (v23.0, SPSS Inc, USA), one-way repeated measures Analyses of Variance (ANOVAs) were undertaken to identify differences between the mean number of points played of each rally length, for men and women respectively, with the Greenhouse-Geisser correction used if the assumption of sphericity was violated (Field, 2013). Bonferroni post-hoc tests were conducted, and effect sizes for ANOVAs (η^2) and post-hoc tests (Cohen's *d*) calculated. Effect sizes are defined as follows: $\eta^2 \geq 0.01$ is small, ≥ 0.06 is medium, ≥ 0.14 is large (Cohen, 1988); Cohen's $d \geq 0.2$ is small, ≥ 0.5 is medium, ≥ 0.8 is large (Cohen, 1988). Note that results of the main ANOVAs and associated effect sizes are presented in the results section; full results of the post-hoc testing (pairwise comparisons) and Cohen's *d* effect sizes are detailed in Appendix B. To provide context, the number of points played of each individual rally length in each match was also normalised to a percentage of short points played per match, then the mean percentage of points played of each rally length was calculated for men and women, respectively.

Derived from the 'point winner' and 'match winner' data, a new column was calculated to establish which player won each respective point; the match winner (coded '1') or the match loser (coded ‘0’). Then, the total number of points of each rally length won by the winning player and the losing player, respectively, was summed at match-level. Replicating the method presented in previous chapters, the *Percentage of matches in which the Winner Outscored the Loser* (PWOL) was calculated for each rally length, for men and women, to establish associations with match outcome. PWOL interpretation is defined in Table 5.2. (Chapter 5).

8.3. Results

Table 8.1. displays the mean number of points played (per match) of each individual rally length, for both sexes. For context, Figure 8.1. shows these values normalised to percentages of the total number of short points played per match.

Table 8.1. *Mean (± sd) number of points played per match of each rally length, by both sexes.*

	Mean number of points played per match	
Rally length	Men	Women
0 shots	$7.5 \pm 3.8^{*}$	$6.2 \pm 3.5^{+}$
1 shot	$76.3 \pm 29.6^{*}$	$34.4 \pm 13.2^{+}$
2 shots	$25.4 \pm 9.6^{*}$	$19.1 \pm 7.4^{+}$
3 shots	$36.3 \pm 13.2^{*}$	$20.9 \pm 7.9^{+}$
4 shots	$17.7 \pm 6.1^{*}$	$13.5 \pm 5.7^{+}$

* Different from the number of points played of all other rally lengths, for men ($p < 0.001$).
$^{+}$ Different from the number of points played of all other rally lengths, for women ($p < 0.01$).

One-way repeated measures ANOVAs revealed a difference in the prevalence of each rally length for men $F(1.419, 297.909) = 951.074$, $p < 0.001$, $\eta^2 = 0.819$, and women $F(2.502, 520.391) = 566.181$, $p < 0.001$, $\eta^2 = 0.731$, respectively. As denoted in Table 8.1., post-hoc testing revealed differences between all pairs of rally lengths (for full details, see Appendix B). Table 8.1. and Figure 8.1. show that *1 shot* was the most common rally length for male and female players, with *3 shots* the second most common rally length. The least common rally length for both sexes was *0 shots*.

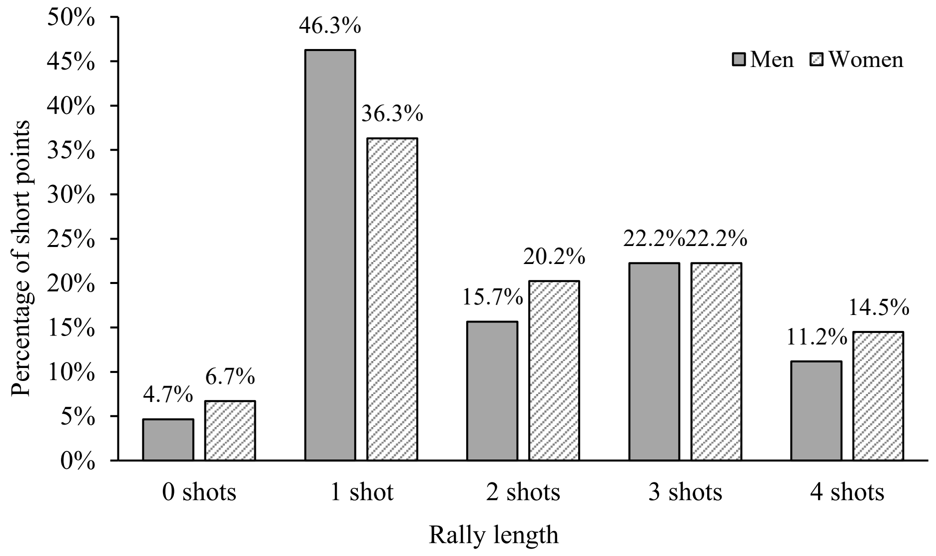


Figure 8.1. *Mean percentage of points played per match of 0, 1, 2, 3 and 4 shot rally lengths, for men and women.*

Table 8.2. shows the mean number of points won of each individual rally length (per match) by winning and losing players, respectively, and corresponding PWOLs, for both sexes. For context, *points won of 0-4 shot rally length* (as presented in Chapter 5) is also included.

Table 8.2. *Mean (± sd) number of points won of each rally length by winning and losing players of both sexes, and corresponding PWOLs.*

	Men			Women		
Rally length	Winning players	Losing players	PWOL	Winning players	Losing players	PWOL
0 shots	4.2 ± 2.7	3.2 ± 2.4	56%	3.5 ± 2.2	2.7 ± 2.3	55%
1 shot	41.3 ± 15.5	35.0 ± 16.2	71%	18.9 ± 7.0	15.4 ± 7.5	71%
2 shots	15.1 ± 5.9	10.4 ± 5.3	77%	11.0 ± 4.3	8.1 ± 4.4	71%
3 shots	18.3 ± 7.2	18.0 ± 7.7	48%	11.0 ± 4.3	9.9 ± 4.8	54%
4 shots	10.6 ± 3.7	7.1 ± 3.7	72%	7.8 ± 3.5	5.9 ± 3.2	66%
0-4 shots (total)	89.5 ± 25.7	73.7 ± 28.6	92%	52.3 ± 14.3	41.8 ± 16.7	87%

Table 8.2. shows that, of the five individual rally lengths, *points won of 1 shot, points won of 2 shots* and *points won of 4 shots* were associated with winning matches, whereas *points won of 0 shots* and *points won of 3 shots* were not associated with match outcome. As demonstrated

in Chapter 5, the combination of all five rally lengths (i.e. *points won of 0-4 shot rally length*) was strongly associated with winning matches for both sexes. No rally lengths were associated with losing matches.

8.4. Discussion

The aims of this study were to identify the prevalence of each individual rally length within short points (*0 shots*, *1 shot, 2 shots*, *3 shots* and *4 shots*) and establish their importance in terms of winning matches, for players of both sexes at Wimbledon. For men and women, the most common rally length was *1 shot*, and the least common was *0 shots*. *Points won of 1 shot, points won of 2 shots* and *points won of 4 shots* were associated with winning matches for both sexes and can therefore be considered important. However, with PWOLs between 40% and 60%, *points won of 0 shots* and *points won of 3 shots* were not associated with match outcome and are therefore not important in terms of winning. These results help to provide a more detailed insight into the importance of short points at Wimbledon, for coaches and practitioners. Results are discussed in ascending order of rally length.

8.4.1. Rally length of *0 shots*

For players of both sexes, *0 shots* was the least common of the five individual rally lengths, comprising less than 5% of all short points for men and less than 7% of all short points for women. *Points won of 0 shots* were not associated with match outcome for either sex, and can therefore be considered not important in terms of winning matches at Wimbledon. Based on the rally length definition provided, a rally length of *0 shots* occurs when the server hits a double fault; hence, so the returner is the only player who can win a rally of *0 shots*. The low prevalence of *0 shots* points here support the low prevalence of double faults reported by Filipcic et al. (2008) in elite clay court tennis (mean ≤ 2.11 per player per match, for men and women). However, at Roland Garros it was demonstrated that match winners committed fewer double faults than match losers (Filipcic et al., 2008), whereas here, *points won of 0 shots* did not differentiate between winners and losers. With *0 shots* being the least common of the five rally lengths, the lack of importance of *points won of 0 shots* can be expected.

Note that the PWOLs for men's and women's *double faults* reported in Chapter 5 (both 38%, Table 5.3.) were different to the PWOLs for *points won of 0 shots* here – there are three reasons for this. Firstly, the samples were not identical; this sample included only matches played on courts where a serve speed radar was available, whereas all completed matches were included in the Chapter 5 sample. Secondly, the two values that are compared at match-level in order for PWOL to be calculated are reversed when establishing which player hit more double faults, compared to which player won more points of 0 shots. So, theoretically, the PWOL for *points won of 0 shots* should be equal to (100 – PWOL for *double faults*). In practice however, this is not necessarily true, as when both players in a match hit an equal number of double faults, the PWOL calculations are influenced differently. For example, if the winning player hits more double faults than the losing player in 35 out of 100 matches, but the two players hit an *equal* number of double faults in 5 matches, the PWOL for *double faults* would be 35%, while the PWOL for *points won of 0 shots* would be 60%. For this reason, it is important that practitioners understand the context around PWOL values when interpreting results, particularly for those performance characteristics with a higher likelihood of two players in a match exhibiting the same value (such as double faults, due to their low prevalence).

8.4.2. Rally length of *1 shot*

For both sexes, *1 shot* was the most common rally length, comprising almost half of all short points in the men's game and over a third in the women's game. *Points won of 1 shot* were associated with winning matches for both sexes and can therefore be considered important. A rally length of *1 shot* occurs when either the serve (i.e. the first stroke) is an ace, or the serve-return (i.e. the second stroke) is an error; either way, the server wins the point. So, results show that players who utilised their serve more often to gain a tactical advantage (i.e. created a perturbation by destabilising the dynamic equilibrium of the point) that led to them immediately winning the point, either with an ace or a missed serve-return, won the match in over 70% of cases. Several previous studies have subjectively suggested that the serve is one of, if not the most important stroke in tennis (O'Donoghue & Brown, 2008; Bollettieri, 2015; Mecheri et al., 2016; Ruder, 2019). The results presented in Chapter 5 supported those claims, and results in this chapter provide further evidence of the importance of the serve.

With the high prevalence of the *1 shot* rally length, the importance of *points won of 1 shot* can be expected. The high prevalence of the *1 shot* rally length exemplifies the difficulty of returning serves on grass courts, particularly for men; as identified by Meffert et al. (2018), the low and fast bounce (compared to other court surfaces) gives serving players a greater advantage at the start of each point. From a practical perspective, there are several aspects of the serve that players can manipulate to attempt to gain a tactical advantage, such as ball speed (Vaverka & Cernosek, 2016; Meffert et al., 2018), ball spin (Bollettieri, 2015), ball placement (Shelton et al., 2016) and technical disguise (Newman & Crespo, 2008). It is crucial for players to develop an understanding of both how and when is most appropriate to exploit each of these factors, to enhance their likelihood of success.

8.4.3. Rally length of *2 shots*

For men and women, *2 shots* was the third most common rally length. Additionally, *points won of 2 shots* were associated with winning matches for both sexes and can therefore be considered important at Wimbledon. A rally length of *2 shots* occurs when the returner hits a winner on the serve-return, or when the server makes an error on their second stroke (i.e. the third stroke of the rally); the returner wins the point in both cases. So, the importance of *points won of 2 shots* revealed here highlights the importance of the serve-return stroke.

Several aspects contribute to the successful execution of serve-returns in tennis, with anticipation (Filipcic et al., 2017), reaction time and movement speed (Vernon et al., 2018) particularly crucial. Results indicate that players who excel in these areas, and can therefore return their opponent's serve more effectively (i.e. by putting them under immediate time or positional pressure by hitting a direct winner or forcing the server to commit an error), win the match in the majority of cases. This is supported by Vernon et al.'s (2018) exploration of the anticipation sources used by elite tennis players when returning serves. Participants (former and current elite male players) explained that the best returners are able to take the ball early and move into the court when striking the serve-return, allowing them to hit the ball harder and more accurately, especially on important points (Vernon et al., 2018). In theory, this may sound like a relatively simple task, but in practice, it is a risky strategy that can be difficult to execute successfully (Bollettieri, 2015), as the serve tends to be an effective weapon for most players. In turn, returning players can face considerable time constraints and are often required to perform the serve-return in a biomechanically suboptimal body position (Gillet et al., 2009). Therefore, the likelihood of the returning player not only neutralising the serve (i.e. re-establishing the dynamic equilibrium of the point), but immediately countering with an attacking serve-return that the server will be unable to retrieve, is small. Second serves (as opposed to first serves) typically present the best opportunity for returning players to execute this type of strategy successfully, as most elite players opt for a faster first serve, slower second serve strategy, when serving (McMahon & de Mestre, 2002; Barnett et al., 2008; Pollard, 2008). With this 'fast-slow' serving strategy, second serves travel comparatively slower through the air, which affords the returning player more time to position themselves optimally to execute an attacking serve-return. For this reason, first serve points and second serve points will be analysed separately in Chapter 9 (limitations of the current dataset prevented their stratification). It is also worth noting that in the men's game, *points won of 2 shots* appear to have been particularly decisive and influential to the outcome of matches at Wimbledon, with a PWOL of 77%. This may be considered surprising, as only 15.7% of short points had a rally length of *2 shots*; based on this result, it could be argued that the serve-return is more crucial than the serve for male players at Wimbledon, which supports Vernon et al.'s (2018) assertion that the serve-return is the "most influential situation" in tennis.

8.4.4. Rally length of *3 shots*

A rally length of *3 shots* occurs when the server hits a winner on their second stroke (i.e. the third stroke of the rally) or the returner makes an error on their second stroke (i.e. the fourth stroke of the rally); the server wins the point in both instances. For players of both sexes, *3 shots* was the second most common rally length. Despite this, *points won of 3 shots* were not associated with match outcome for either sex. In elite tennis, the serving player can attempt to use their serve to tactically 'set up' the point, by aiming their serve close to the side line (i.e. wide) and taking their opponent away from the centre of the court in order to create free space to exploit with their second stroke (Brown, 2004). From the server's perspective, this type of attacking combination, involving the serve, (the serve-return) and the server's second stroke is often referred to as a 'serve plus one' strategy (e.g. Miron, 2018; Anderson, 2018a; Frausto, 2019). Although no empirical research has specifically investigated serve plus one strategies, tennis practitioners anecdotally consider them to be crucial components of an elite tennis player's arsenal (Anderson, 2018b; Palmer, 2019; O'Shannessy, 2019c). Despite this, the PWOLs for men's and women's *points won of 3 shots* show that serve plus one strategies did not differentiate winning and losing players. Given their perceived importance among tennis practitioners, it is possible that serve plus one strategies are not differentiating factors because they are so heavily practised by all elite players, hence winning and losing players perform them equally as well as each other during match-play. In turn, this presents a challenge to coaches and players, who must decide how much time to spend practicing serve plus one strategies during grass court training sessions, given that they did not differentiate winning and losing players at Wimbledon. In contrast, *points won of 1 shot* and *points won of 2 shots* did differentiate winning and losing players. Therefore, coaches may wish to focus more on aspects such as the serve and serve-return in training, as this may be more likely to give players an advantage over opponents during match-play. Such adaptations to the design of practice must be carefully considered however, as, crucially, *under*-practising serve plus one strategies may cause a player to fall behind fellow competitors in their execution of 3 shot rallies.

8.4.5. Rally length of *4 shots*

Of the five individual rally lengths, *4 shots* was the fourth most common for both sexes; only *0 shots* occurred less often. Despite this, *points won of 4 shots* were associated with winning matches for both sexes, with PWOLs of 72% for men and 66% for women, and should therefore be considered important. A rally length of *4 shots* occurs when the returner hits a winner on their second stroke (i.e. the fourth stroke of the rally) or the server makes an error on their third stroke (i.e. the fifth stroke of the rally); the returning player always wins the point. This demonstrates that, in addition to serving strategies, returning strategies are important at Wimbledon. However, while serve plus one strategies (i.e. strategies for the serving player) have often been afforded attention on tennis media platforms (e.g. Miron, 2018; Anderson, 2018b; Palmer, 2019; O'Shannessy, 2019c), equivalent strategies for returning players are seldom mentioned (for two exceptions, see O'Shannessy, 2017a and Annacone, 2018). This could indicate a (mis)perception among practitioners that returning strategies are less important for elite players than serving strategies. One reason for this perception may be that the serving player, rather than the returning player, controls the beginning of each point (United States Tennis Association, 2009). From an ecological dynamics and constraints-led perspective, the returner's behaviour or strategy emerges, then, partially as a result of the server's strategy. This could imply that the returning player has limited influence over their serve-return, and therefore that planning a returning strategy might be futile. However, it is important to note that strategy and tactics are also constraints (Davids et al., 2005), which, as part of the interaction of constraints perceived by the returning player, intrinsically influence and contribute to their emergent behaviour. Additionally, it is possible for the returning player to influence the server's strategy and subsequent serve performance; elite players have reported using movement and court positioning while waiting to return serve, to put pressure on the server and force them to doubt and/or reconsider their planned serving strategy (Vernon et al., 2018). For these reasons, the importance of returning strategies should not be overlooked by coaches, when planning appropriate training practices and match-play strategies for their players.

Tennis players have also reflected that, not only is the serve-return an under-practiced stroke, but also that its practice is not sufficiently specific (Vernon et al., 2018). Elite players suggested that junior competitors would benefit from increased exposure to different serve types and trialling alternative serve-return positions during training, to enhance their awareness of contextual and kinematic information sources and develop adaptability as returners (Vernon et al., 2018).

It is worth noting that the PWOLs for *points won of 2 shots* and *points wo of 4 shots* were 6% higher for men than for women. This suggests that the serve-return and associated strategies are more important for men than for women on grass courts. This is likely linked to the commonly reported differences in serve speed between the two sexes. As men typically serve faster than women (Crespo & Miley, 1998; Cross, 2014; Carboch, 2017), male returners have comparatively less time to react and execute the serve-return (Reid et al., 2016). With these stricter time constraints, it could be argued that returning is a more difficult skill for men, and therefore that being a proficient male returner affords a greater advantage over opponents than being a proficient female returner (as more women are likely capable of satisfying the constraints of the serve-return), hence men's higher PWOLs. This would also explain why women are able to successfully execute a higher percentage of serve-returns into play and why their serve-return speed has been shown to be higher than men's (Reid et al., 2016), as women have comparatively more time to adopt an appropriate court position and prepare to execute the stroke.

8.5. Conclusion

This study has provided new insights into the prevalence and importance of points of different rally lengths in elite grass court tennis. Irrespective of sex, *1 shot* was the most common rally length, and *points won of 1 shot* were important in terms of winning matches, which affirms the importance of the serve and associated serving strategies. *Points won of 2 shots* and *points won of 4 shots*, both of which are won by the returning player, were also important, thus suggesting that the serve-return and associated returning strategies are important and should be afforded focus within grass court training. In contrast, *points won of 3 shots* did not differentiate winning and losing players, which challenges anecdotal claims that serve plus one strategies are crucial in elite tennis. Results from this study can inform coaches and practitioners aiming to plan training sessions that are more representative of elite men's and women's grass court match-play, and exhibit high specificity. Future research into the serving and returning strategies employed by elite players would further facilitate this application and potentially reveal the most common and most successful (and unsuccessful) serving and returning strategies; Chapter 9 will explore these aspects.

Chapter 9

Analysing Hawk-Eye ball-tracking data to explore the serving and returning strategies used at Wimbledon

This study was informed by the work presented in Chapters 5, 6 and 7, and is a progression of the short points analysis presented in Chapter 8. In this chapter, ball-tracking data are analysed to explore the serving and returning strategies used by male and female players at Wimbledon, and identify associated winner-loser differences.

9.1 Introduction

Originally, the recording of tennis notational analysis data was limited to basic characteristics such as stroke type, point outcome and rally length due to a lack of automated techniques (Mecheri et al., 2016), and as these measure were sufficiently objective to be recorded live with good reliability. In recent years, technological advancements, including the development of Global Positioning Systems (GPS) and automated tracking software, have increased our capacity to collect a wider range of performance characteristics (Mecheri et al., 2016). For example, Hawk-Eye technology (Hawk-Eye Innovations ltd, Basingstoke, UK) has enabled automated, ball-tracking data collection, on a shot-by-shot basis. Hawk-Eye uses up to ten high-speed (60Hz) calibrated cameras to continually track the location of a tennis ball during a match. The system was originally introduced to allow players to 'challenge' line calls made by match officials (Kolbinger & Lames, 2013), but its implementation has also benefitted those in coaching, research, broadcasting and digital media professions, as well as enhancing fan engagement (Hawk-Eye, 2020). From a research perspective, Hawk-Eye has facilitated the collection of a wealth of performance data and, in turn, provided extensive opportunities for analysis (Reid et al., 2016). Wimbledon installed Hawk-Eye camera systems on Centre Court and Court One in 2007, and by 2015, the technology was in place on six courts (Hawk-Eye, 2015a), allowing data to be collected from a more representative sample of elite tennis matches.

Thus far, studies analysing Hawk-Eye data in tennis have investigated the influence of serve characteristics (serve speed and spin rate of the ball) on point-winning probability (Mecheri et al., 2016), identified the different types of strokes performed by elite players (Kovalchik & Reid, 2018), compared the technical and physical demands of junior and senior match-play (Kovalchik & Reid, 2017), and established sex differences in stroke and movement dynamics on hard courts (Reid et al., 2016). Results from these studies have facilitated several practical applications, with perhaps the most relevant for coaches being provided by Reid et al. (2016), who were able to inform sex-specific training designs for elite players preparing for the hard-court season. These authors also highlighted the importance of future research investigating tennis Hawk-Eye data, to assist those practitioners who are aiming to provide more evidence-based training programmes (Reid et al., 2016).

Previous work in this thesis demonstrated that *points won of 0-4 shot rally length* (i.e. short points) was the most important performance characteristic at Wimbledon, irrespective of sex (Chapter 5), time (Chapter 5) and match closeness (Chapter 6), and that the serve and serve-return are crucial for winning short points (Chapter 8). Further emphasising the importance of the serve and serve-return in elite tennis, Antoun (2007) observed that traditional gamestyles (e.g. serve-volleying, baseline play, all-court play) have become less relevant, and highlighted that the aim for most current players is to gain control of the point as early as possible. To do this, players often execute pre-planned strategies, whereby each stroke is hit to a specific area of the court. The key to successful strategies is understanding where to direct the ball, such that each stroke builds on the previous stroke (Antoun, 2007). For example, a particular serve may be executed to elicit a specific serve-return from the opponent, which the server can anticipate, allowing them to better prepare for their next stroke (Rive & Williams, 2011).

Existing investigations into the serving and returning strategies executed by elite players are limited. Gillet et al. (2009) analysed elite men's serving and returning strategies on clay courts, but television recordings were used to estimate the ball landing location of each stroke (and infer serve and serve-return strategies), the reliability of which is questionable (Yan, 2007). Mecheri et al. (2016) investigated serving strategies, reporting that players tended to aim their first serves close to the lateral edges of the service box and their second serves towards the opponent's backhand, however, their analysis was not stratified by court surface, making surface-specific interpretations difficult. Other serve and serve-return based studies were undertaken prior to the introduction of Hawk-Eye technology and were therefore restricted in their sample size (e.g. n = 8 matches Taylor & Hughes, 1998; n = 2 matches Unierzyski & Wieczorek, 2004). Since the introduction of Hawk-Eye, no published study has sought to identify the serving and returning strategies executed by elite male and female players on grass courts. Such an investigation would contribute to a more holistic understanding of the importance of short points at Wimbledon, and provide valuable insight into how these points are typically won. Such analysis would also better inform coaches in their attempts to develop representative learning environments and effectively prepare players for grass court competitions (Reid et al., 2016).

Therefore, this study analyses Hawk-Eye ball-tracking data, to identify the most prevalent and the most effective (i.e. successful) serving and returning strategies executed by elite male and female players at Wimbledon, as well as establishing whether these strategies differ between winning and losing players.

9.2. Method

9.2.1. Data collection

Institutional ethics approval was granted for this study. Prior to the data collection, Hawk-Eye's technical operators calibrated the dimensions of each court and defined a right-handed court reference frame, with its origin at the base of the centre of the tennis net. The three-dimensional Cartesian coordinates, relative to the reference frame, of the ball-racket impact (i.e. ball contact location) and ball-court impact (i.e. ball landing location) were obtained for every stroke in 302 men's and 139 women's Wimbledon singles matches contested between 2015 and 2017 on one of the six courts equipped with Hawk-Eye technology. In addition to the ball coordinate data, the following information was obtained for each stroke: year, match ID, point ID, server of the point, whether the point started with a first serve or a second serve, and stroke number (in the context of an individual point). Due to the nature of these data, reliability testing was not possible, however the accuracy of Hawk-Eye ball-tracking technology has been independently validated, with a reported mean error of 2.6 mm, compared to a gold standard (Hawk-Eye, 2015b).

9.2.2. Data processing

Using a custom MATLAB (MathWorks, Natick, MA) script, several stages of data processing, cleaning and error detection were undertaken. Coordinate data were processed such that all strokes performed by serving players should originate from one side of the net, and all strokes performed by returning players should originate from the opposite side of the net. Erroneous coordinates were then identified, and all associated data (i.e. those within the same point) removed. The following types of erroneous data were removed; i) instances when the ball contact location of a stroke and the ball landing location of that stroke were on the same side of the net, ii) instances when the ball contact location of a stroke was on the opposite side of the net to the ball landing location of the previous stroke, iii) instances when the ball contact location of a stroke was on the same side of the net as the ball contact location of the previous stroke, and iv) instances when the ball landing location of a stroke was on the same side of the net as the ball landing location of the previous stroke. Approximately 2.5% of match-play points were removed from the dataset accordingly.

Within the MATLAB script, serves, volleys (i.e. any stroke whereby the player contacted the ball prior to the ball bouncing), serve side (i.e. deuce or advantage court) and errors (i.e. unsuccessful strokes that landed in the net or out of the court) were identified. The ball landing coordinates of successful strokes were then analysed to establish which area (i.e. zone) of the court the ball landed in (see Figure 9.1.).

Note that the zones for the advantage court service box do not ‘mirror’ the zones for the deuce court service box. Instead, serve zone is viewed from the perspective of a right-handed returner[1], whereby a serve to zone A is designed to evoke a forehand return, and a serve to zone D is designed to evoke a backhand return, irrespective of serve side (i.e. deuce or advantage court). This ‘ABCD’ zone labelling technique has been advised by O’Shannessy (2019c) to better understand tennis strategy. Next, stroke-level data were processed and aggregated to derive point-level data (n = 53,328 men’s points, n = 16,689 women’s points), including serve side, first or second serve, rally length, match winner, point winner (i.e. match winner or match loser, and serving player or returning player), and ball landing zone of the serve and serve-return.

Note also that ball landing locations are henceforth referred to as ‘serving strategies’ for serve zones A, B, C and D, and ‘returning strategies’ for wide and central serve-return zones. Additionally, deuce court first serves, deuce court second serves, advantage court first serves, and advantage court second serves are collectively referred to as ‘serve types’, and corresponding serve-returns are referred to as ‘return types’, for conciseness.

Serve-returns were originally analysed according to the combination of serve zone (A, B, C or D) and subsequent serve-return zone (A, B, C or D), i.e. creating a two-letter sequence for each point. However, serve-return results did not differ by serve zone, and statistical analysis (partitioned chi squares) showed that serve-return zone could be partially collapsed. Therefore, to increase sample size and aid interpretation, serve zone was omitted from the serve-return analysis and serve-return ball landing zones were reclassified as ‘wide’ (i.e. previously zones A and D) and ‘central’ (i.e. previously zones B and C), as shown in Figure 9.1.

[1] Right-handed players comprised an average of 85% of men’s top 100 players and 92% of women’s top 100 players each year between 2015 and 2017 (ATP, 2020; WTA, 2020).

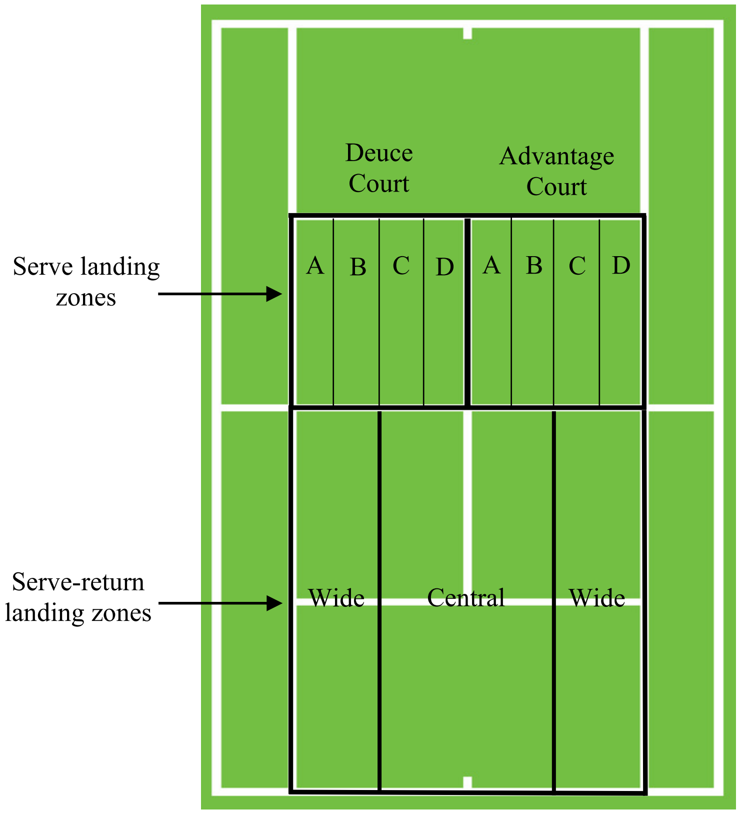


Figure 9.1. *Serve and serve-return ball landing zones (i.e. strategies).*

The summary statistics listed in Table 9.1. were calculated for men and women using the calculations presented. The calculations in Table 9.1. pertain to serve zone A and the central serve-return zone on deuce court first serve points, but results were calculated for all respective serve types, serve zones and, where appropriate, return types and serve-return zones.

Table 9.1. *Definitions and calculations used to calculate key summary statistics.*

Summary statistic	Definition/calculation
Serving strategy prevalence n	Total number of deuce court first serves to zone A
Serving strategy prevalence (%)	Number of deuce court first serves to zone A/number of successful deuce court first serves x 100
Serving strategy success rate (%)	Number of points won by the serving player following a deuce court first serve to zone A/number of deuce court first serves to zone A x 100
Serving strategies of winning players (%)	Number of deuce court first serves to zone A executed by match winners/total number of deuce court first serves executed by match winners x 100
Serving strategies of losing players (%)	Number of deuce court first serves to zone A executed by match losers/total number of deuce court first serves executed by match losers x 100
Serve-volley strategy prevalence n	Total number of deuce court first serves to zone A whereby the server's second stroke was a volley.
Serve-volley strategy success rate (%)	Number of serve-volley points won by the serving player following a deuce court first serve to zone A/number of serve-volley points played following a deuce court first serve to zone A x 100
Returning strategy prevalence n	Total number of deuce court first serve-returns to central zones.
Returning strategy prevalence (%)	Number of deuce court first serve-returns to central zones/number of successful deuce court first serve-returns x 100
Returning strategy success rate (%)	Number of points won by the returning player following a deuce court first serve-return to central zones/number of deuce court first serve-returns to central zones x 100
Returning strategies of winning players (%)	Number of deuce court first serve-returns to central zones executed by match winners/total number of deuce court first serve-returns executed by match winners x 100
Returning strategies of losing players (%)	Number of deuce court first serve-returns to central zones executed by match losers/total number of deuce court first serve-returns executed by match losers x 100

9.2.3. Data analysis

All analyses detailed in this section were undertaken on men's and women's data, respectively. Due to the complexity of the data, several analysis methods, each explained below, were required.

Upper and lower bounds for the prevalence of each serving strategy were calculated using sample size, based on 99% confidence intervals (Sullivan & LaMorte, 2016). These bounds were used to identify differences in the prevalence of serving strategies for each serve type, respectively.

Chi-square analyses were undertaken to establish whether success rates differed between serving strategies (i.e. zones A, B, C and D), for each respective serve type. Where differences were identified, the overall chi-square was partitioned, as a form of post-hoc analysis (Maxwell, 1961; Bresnahan & Shapiro, 1966; Sharpe, 2015), to identify where the differences were (i.e. between which zones). Similarly, chi-square, and chi-square partitions when appropriate, were used to identify differences in the prevalence and success rates of returning strategies (i.e. wide and central zones), and whether serving and returning strategies differed between winning and losing players.

Statistical analysis of serve-volley prevalence and success rates was not undertaken due to the limited number of points in which players serve-volleyed (men: n = 1751 points, 3.3% of total points; women: n = 175 points, 1.0% of total points). Using the Hawk-Eye dataset, it was only possible to identify a serve-volley point if the serving player successfully executed a volley (i.e. when the rally length was ≥ 3 shots). However, a player can perform a serve-volley point without successfully executing a volley, if they approach the net after their serve, but either the serve is an ace (rally length = 1 shot), the serve-return is an error (rally length = 1 shot), the serve-return is a winner (rally length = 2 shots), or the volley is an error (rally length = 2 shots).

Accordingly, projections were calculated, in the following stages, to estimate the number of serve-volley points executed. First, the percentage of total points whereby the rally length was ≥ 3 shots was calculated for each serve zone and serve type, respectively (as this rally length was the identifiable portion of serve-volley points). Then, the percentage of total points that were of 1 shot rally length (i.e. won by serving players) and 2 shot rally length (i.e. won by returning players) was calculated for each serve zone and serve type. Finally, these percentages were applied to the serve-volley data as a form of extrapolation, to enable projected serve-volley prevalence and success rates to be calculated for each serve type-serve zone combination. Although these projected values were likely to be more accurate than the original serve-volley prevalence and success rates, the approach was novel, so no statistical analysis was undertaken, and associated results should be interpreted with caution.

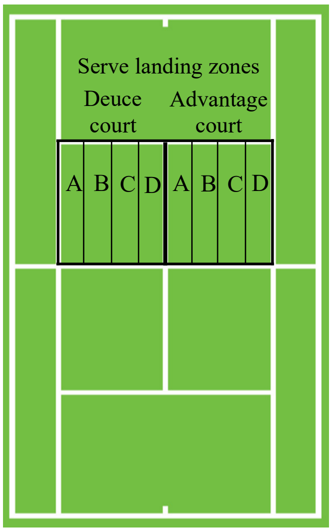
9.3. Results

9.3.1. Serving strategies: prevalence and success rates

Table 9.2. displays the prevalence (as a frequency and percentage) and success rate (percentage of points won by serving players) for each serve type and serving strategy (i.e. zones A, B, C and D) for men.

Table 9.2. *Men's prevalence and success rate (i.e. percentage of points won by serving players) for each serving strategy.*

Serve side	Serve and serve zone	Prevalence n (%)	Server success rate (%)
Deuce court	First serve		
	A	6985 (37.9%) [b]	76.1% [2]
	B	1860 (10.1%) [c]	61.7% [3]
	C	1847 (10.0%) [c]	64.8% [3]
	D	7751 (42.0%) [a]	77.9% [1]
	Second serve		
	A	1357 (14.5%) [c]	65.5% [1]
	B	1776 (19.0%) [c]	53.6% [3]
	C	3601 (38.4%) [a]	54.0% [3]
	D	2637 (28.1%) [b]	59.2% [2]
Advantage court	First serve		
	A	7078 (42.5%) [a]	73.4% [2]
	B	1341 (8.0%) [d]	63.1% [3]
	C	2196 (13.2%) [c]	60.5% [3]
	D	6045 (36.3%) [b]	79.7% [1]
	Second serve		
	A	1711 (19.3%) [b]	60.5% [1]
	B	1649 (18.6%) [b]	55.9% [2]
	C	3479 (39.3%) [a]	55.1% [2]
	D	2015 (22.8%) [b]	60.3% [1]



[a-d] Denotes the order of prevalence, based on statistical analysis, from most prevalent serving strategy to least prevalent serving strategy, for each serve type, respectively.

[1-3] Denotes the order of success rate, based on statistical analysis, from most successful serving strategy to least successful serving strategy, for each serve type, respectively.

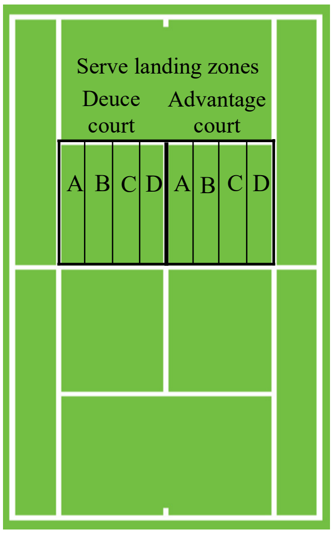
Table 9.2. shows differences in the prevalence of serving strategies for men. Confidence intervals (CI) calculated at a predetermined significance level of $p < 0.01$ revealed that on deuce court first serves, zone D was the most common serving strategy for men (prevalence = 42.0%, 99% CI [40.6%, 43.5%]), followed by zone A (prevalence = 37.9%, 99% CI [36.4%, 39.4%]). On advantage court first serves, zone A was the most common strategy (prevalence = 42.5%, 99% CI [41.0%, 44.0%]), followed by zone D (prevalence = 36.3%, 99% CI [34.7%, 37.9%]). On second serves, zone C was the most common serving strategy for men in the deuce court (prevalence = 38.4%, 99% CI [36.3%, 40.5%]) and advantage court (prevalence = 39.3%, 99% CI [37.2%, 41.4%]).

Table 9.2. also shows differences in men's serving strategy success rates, χ^2 (3, n = 53,328) = 1315.93, $p < .001$). Chi-square partitions revealed that for all four serve types, zones A and D exhibited higher success rates than zones B and C for men, χ^2 (1, n = 53,328) = 1306.91, $p < .001$. Furthermore, first serves to zone D exhibited higher success rates than first serves to zone A in the deuce court: χ^2 (1, n = 14,736) = 6.48, $p < .05$, and advantage court: χ^2 (1, n = 13,123) = 66.88, $p < .001$. On deuce court second serves, zone A exhibited a higher success rate than zone D, χ^2 (1, n = 3994) = 14.76, $p < .001$.

Table 9.3. displays the prevalence (as a frequency and percentage) and success rate (percentage of points won by serving players) for each serve type and serving strategy (i.e. zones A, B, C and D) for women.

Table 9.3. *Women's prevalence and success rate (i.e. percentage of points won by serving players) for each serving strategy.*

Serve side	Serve and serve zone	Prevalence n (%)	Server success rate (%)
Deuce court	First serve		
	A	1937 (33.5%) [a]	71.0% [1]
	B	879 (15.2%) [b]	59.5% [2]
	C	884 (15.3%) [b]	58.6% [2]
	D	2081 (36.0%) [a]	72.5% [1]
	Second serve		
	A	378 (13.0%) [b]	59.0% [1]
	B	593 (20.4%) [b]	51.4% [2]
	C	1206 (41.5%) [a]	49.3% [2]
	D	732 (25.2%) [b]	55.1% [1]
Advantage court	First serve		
	A	2014 (38.7%) [a]	67.6% [2]
	B	722 (13.9%) [c]	60.4% [3]
	C	939 (18.1%) [c]	57.0% [3]
	D	1523 (29.3%) [b]	73.9% [1]
	Second serve		
	A	509 (18.2%) [b]	53.2% [1]
	B	658 (23.5%) [b]	46.2% [2]
	C	1091 (39.0%) [a]	52.1% [1]
	D	543 (19.4%) [b]	53.6% [1]



[a-d] Denotes the order of prevalence, based on statistical analysis, from most prevalent serving strategy to least prevalent serving strategy, for each serve type, respectively.
[1-3] Denotes the order of success rate, based on statistical analysis, from most successful serving strategy to least successful serving strategy, for each serve type, respectively.

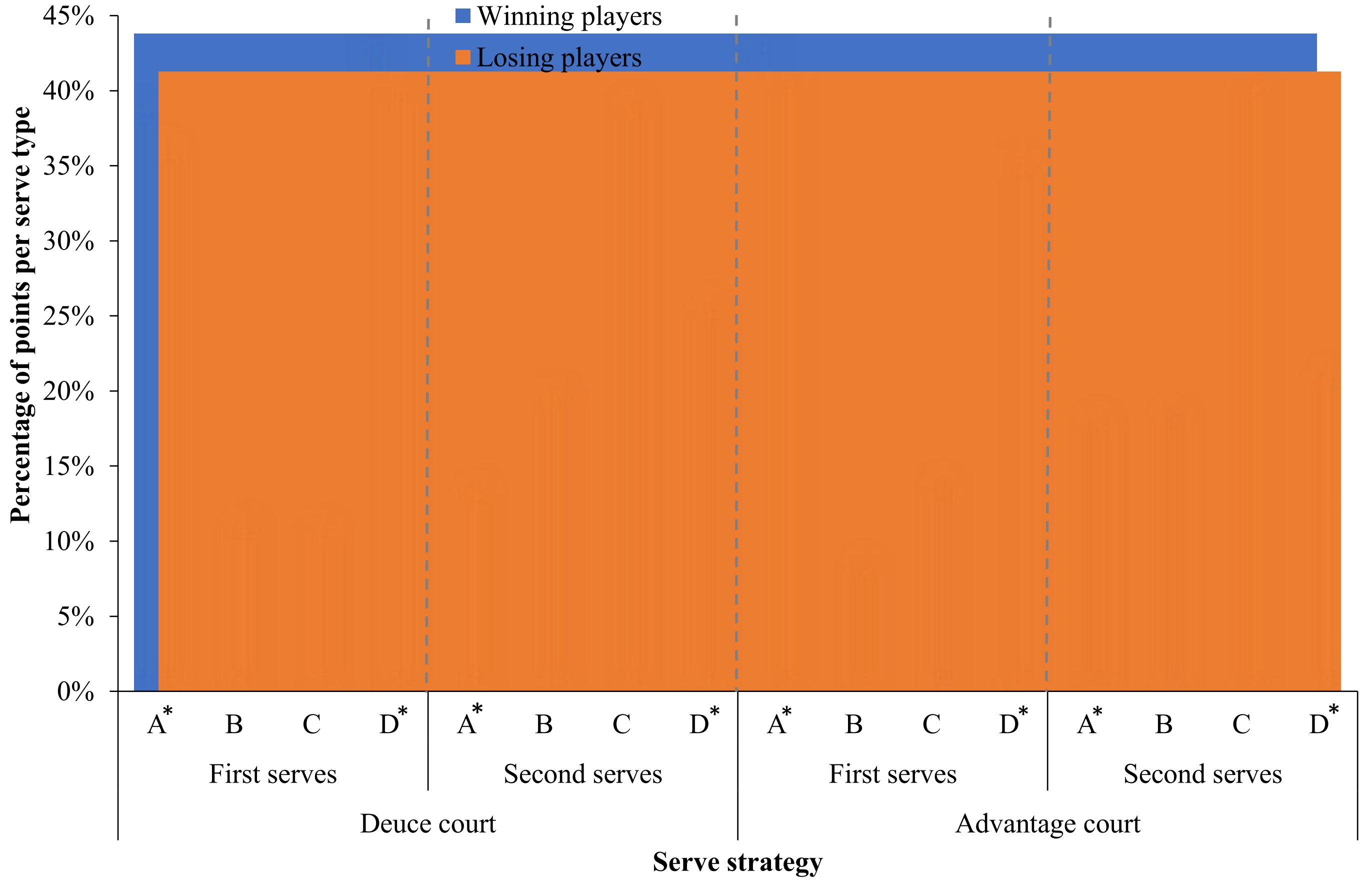
Table 9.3. shows differences in the prevalence of serving strategies. Confidence intervals calculated at a predetermined significance level of $p < 0.01$ indicated that on deuce court first serves, zones A (prevalence = 33.5%, 99% CI [30.7%, 36.3%]) and D (prevalence = 36.0%, 99% CI [33.3%, 38.7%]) were the most common serving strategies for women. On advantage court first serves, zone A was the most common strategy (prevalence = 38.7%, 99% CI [35.9%,

41.5%]), followed by zone D (prevalence = 29.3%, 99% CI [26.3%, 32.3%]). On second serves, zone C was the most common serving strategy for women, in the deuce court (prevalence = 41.5%, 99% CI [37.8%, 45.1%]) and advantage court (prevalence = 39.0%, 99% CI [35.1%, 42.8%]).

Table 9.3. also shows differences in women's serving strategy success rates, χ^2 (3, n = 16,689) = 304.87, $p < .001$). Chi-square partitions revealed that zones A and D exhibited higher success rates than zones B and C for deuce court first serves, χ^2 (1, n = 5781) = 91.10, $p < .001$, deuce court second serves, χ^2 (1, n = 2909) = 11.16, $p < .001$, and advantage court first serves, χ^2 (1, n = 5198) = 71.69 $p < .001$. Within this, zone A exhibited a higher success rate than zone D for advantage court first serves, χ^2 (1, n = 3537) = 15.49, $p < .001$. For advantage court second serves, zone B exhibited lower success rates than zones A, C and D, χ^2 (1, n = 2801) = 8.59, $p < .01$.

9.3.2. Serving strategies executed by winning and losing players

Figure 9.2. displays, for each serve type, the percentage of serves executed to zones A, B, C and D by winning and losing male players, respectively (i.e. serving strategies used by winning and losing male players).

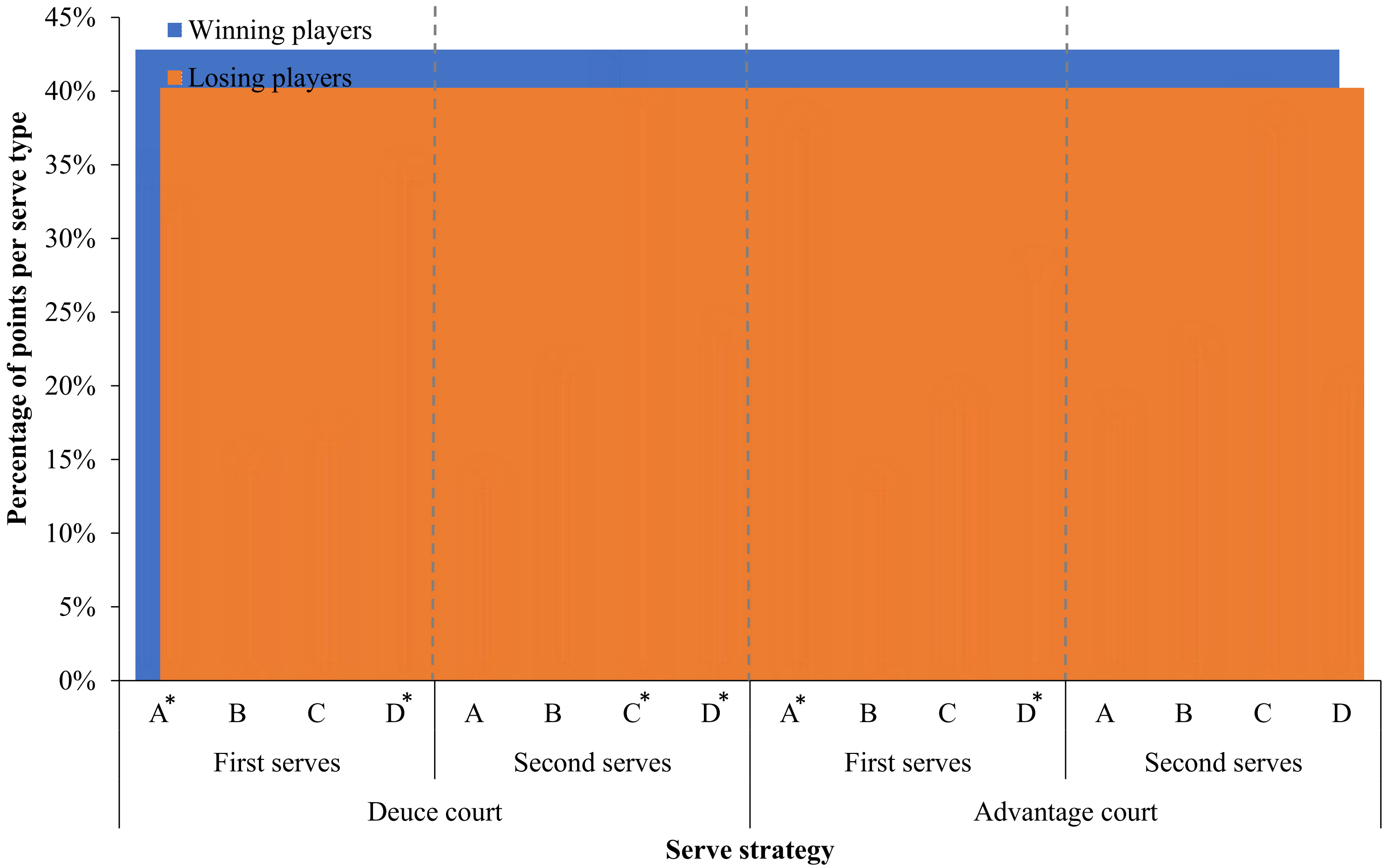


* Zones to which winning male players hit a significantly higher percentage of serves than losing male players ($p < 0.001$).

Figure 9.2. *Serving strategies executed by winning and losing male players.*

Results revealed that serving strategies differed between winning and losing male players, χ^2 (3, n = 53,328) = 169.01, $p < .001$. For all serve types, winning male players executed a greater percentage of their serves to zones A and D (lateral zones) than losing male players, whereas losing players executed a greater percentage of their serves to zones B and C (central zones) than winning players, χ^2 (1, n = 53,328) = 166.82, $p < .001$.

Figure 9.3. displays, for each serve type, the percentage of serves executed to zones A, B, C and D by winning and losing female players, respectively (i.e. serving strategies used by winning and losing female players).



* Zone to which winning female players hit a significantly higher percentage of serves than losing female players ($p < 0.001$).

Figure 9.3. *Serving strategies executed by winning and losing female players.*

Results revealed that serving strategies differed between winning and losing female players, χ^2 (3, n = 16,689) = 10.07, $p < .05$. Chi-square partitions showed that for deuce and advantage court first serves, winning players executed a greater percentage of their serves to zones A and D (i.e. lateral zones) than losing players, deuce court first serves: χ^2 (1, n = 5781) = 12.79, $p < .001$, advantage court first serves: χ^2 (1, n = 5198) = 5.33, $p < .05$. For deuce court second serves, winning players executed a greater percentage of serves to zones C and D than losing players, χ^2 (1, n = 2909) = 7.29, $p < .01$. No differences were observed for advantage court second serves, χ^2 (3, n = 2801) = 2.23, $p > .05$.

9.3.3. Serve-volley strategies: prevalence and success rates

Table 9.4. shows the prevalence and success rates for men's serve-volley strategies for each serve type, and corresponding *projected* values.

Table 9.4. *Men's prevalence and success rate (i.e. percentage of points won by servers) for each serve-volley strategy.*

Serve Side	Serve-volley strategy	Prevalence (n)	Server success rate (%)	*Projected* prevalence (n)	*Projected* server success rate (%)
Deuce court	First serve				
	AV	302	69.9%	*722*	*75.4%*
	BV	73	54.8%	*118*	*57.2%*
	CV	51	62.7%	*86*	*64.9%*
	DV	231	65.4%	*529*	*76.9%*
	Second serve				
	AV	28	75.0%	*57*	*69.9%*
	BV	38	39.5%	*63*	*44.8%*
	CV	44	47.7%	*69*	*49.3%*
	DV	74	58.1%	*115*	*58.1%*
Advantage court	First serve				
	AV	191	53.9%	*403*	*68.9%*
	BV	38	44.7%	*64*	*53.4%*
	CV	71	53.5%	*118*	*55.5%*
	DV	424	71.7%	*1015*	*78.5%*
	Second serve				
	AV	45	42.2%	*77*	*51.1%*
	BV	30	50.0%	*49*	*51.5%*
	CV	49	59.2%	*76*	*56.3%*
	DV	62	61.3%	*114*	*59.2%*

While no statistical analyses were undertaken on men's serve-volley strategies (due to the sample size and limitations associated with identifying serve-volley points using ball coordinate data), *projected* values appear to indicate that serve-volleying to zones A and D may be more prevalent and more successful than serve-volleying to zones B and C on first serve points.

Table 9.5. shows the prevalence and success rate for women's serve-volley strategies for each serve type, and corresponding *projected* values.

Table 9.5. *Women's prevalence and success rate (i.e. percentage of points won by servers) for each serve-volley strategy.*

Serve Side	Serve-volley strategy	Prevalence (n)	Server success rate (%)	*Projected* prevalence (n)	*Projected* server success rate (%)
Deuce court	First serve				
	AV	37	67.6%	*75*	*71.0%*
	BV	5	40.0%	*8*	*46.5%*
	CV	7	57.1%	*11*	*58.1%*
	DV	46	58.7%	*86*	*68.4%*
	Second serve				
	AV	1	100.0%	*2*	*79.0%*
	BV	1	100.0%	*2*	*78.3%*
	CV	1	0.0%	*2*	*17.6%*
	DV	1	100.0%	*2*	*83.5%*
Advantage court	First serve				
	AV	16	31.3%	*29*	*49.9%*
	BV	4	50.0%	*6*	*55.4%*
	CV	7	42.9%	*11*	*47.0%*
	DV	44	70.5%	*90*	*73.8%*
	Second serve				
	AV	2	100.0%	*3*	*81.3%*
	BV	0	N/A	*0*	*N/A*
	CV	2	100.0%	*3*	*81.0%*
	DV	1	0.0%	*2*	*20.0%*

As the sample sizes of several women's serve-volley strategies were extremely low, no description or interpretations were reported.

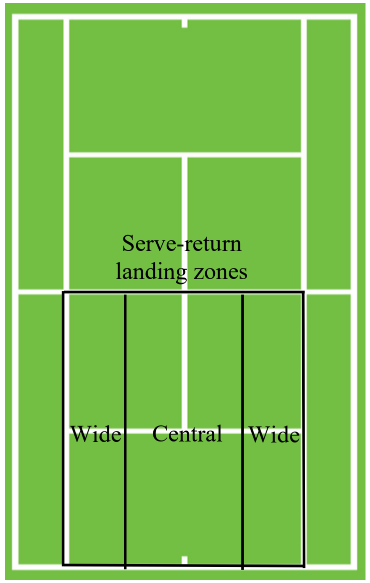
9.3.4. Returning strategies: prevalence and success rates

Table 9.6. displays men's prevalence and success rate (i.e. percentage of points won by returning players) for each returning strategy (i.e. wide and central), for all four return types (i.e. deuce and advantage court first and second serve-returns).

Table 9.6. *Men's prevalence and success rate for each returning strategy.*

Serve side	Return	Return prevalence n (%)		Returner success rate (%)	
		Wide zones (A & D)	Central zones (B & C)*	Wide zones (A & D)^	Central zones (B & C)
Deuce court	First serve-return	3025 (30.9%)	6776 (69.1%)@	52.0%	43.7%
	Second serve-return+	2456 (34.6%)	4642 (65.4%)	61.8%	52.2%
Advantage court	First serve-return	2749 (30.5%)	6251 (69.5%)@	51.9%	44.7%
	Second serve-return+	2551 (38.1%)	4144 (61.9%)	62.9%	50.1%

* Significantly more prevalent than wide zones ($p < .001$).
@ Significantly more prevalent than second serve-returns ($p < .001$).
^ Significantly higher success rates than central zones ($p < .001$).
+ Significantly higher success rates than first serve-returns ($p < .001$).



Chi-square analysis revealed that for all return types, male players hit more serve-returns to central zones (B and C) than wide zones (A and D), χ^2 (3, n = 32,594) = 131.61, $p < .001$, and chi-square partitions showed that this difference was greater on first serve-returns than second serve-returns, χ^2 (1, n = 32,594) = 112.31, $p < .001$. For all return types, serve-returns to wide zones elicited higher success rates for returning players than serve-returns to central zones, χ^2 (3, n = 32,594) = 243.82, $p < .001$; within this, chi-square partitions revealed that second serve-returns elicited higher success rates than first serve-returns, χ^2 (1, n = 32,594) = 242.60, $p < .001$.

Table 9.7. displays women's prevalence and success rate (i.e. percentage of points won by returning players) for each returning strategy (i.e. wide and central), for all four return types.

Table 9.7. *Women's prevalence and success rate for each returning strategy.*

Serve side	Return	Return prevalence n (%)		Returner success rate (%)	
		Wide zones (A & D)	Central zones (B & C)*	Wide zones (A & D)^	Central zones (B & C)
Deuce court	First serve-return	1117 (29.5%)	2669 (70.5%)@	55.1%	45.1%
	Second serve-return+	865 (37.3%)	1453 (62.7%)	67.5%	54.9%
Advantage court	First serve-return	1061 (30.3%)	2436 (69.7%)@	56.5%	45.6%
	Second serve-return+	894 (39.2%)	1389 (60.8%)	67.0%	55.2%

* Significantly more prevalent than wide zones (p<0.001).

@ Significantly more prevalent than second serve-returns (p<0.001).

^ Significantly higher success rates than central zones (p<0.001).

+ Significantly higher success rates than first serve-returns (p<0.001).

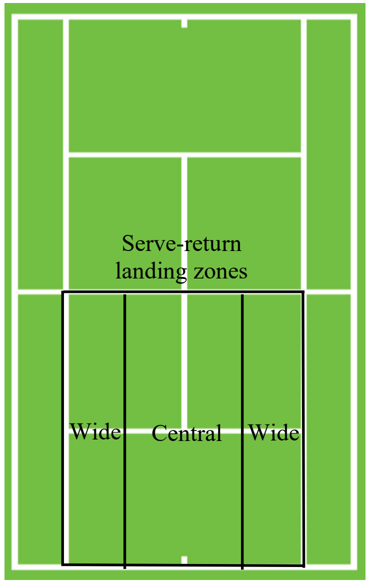
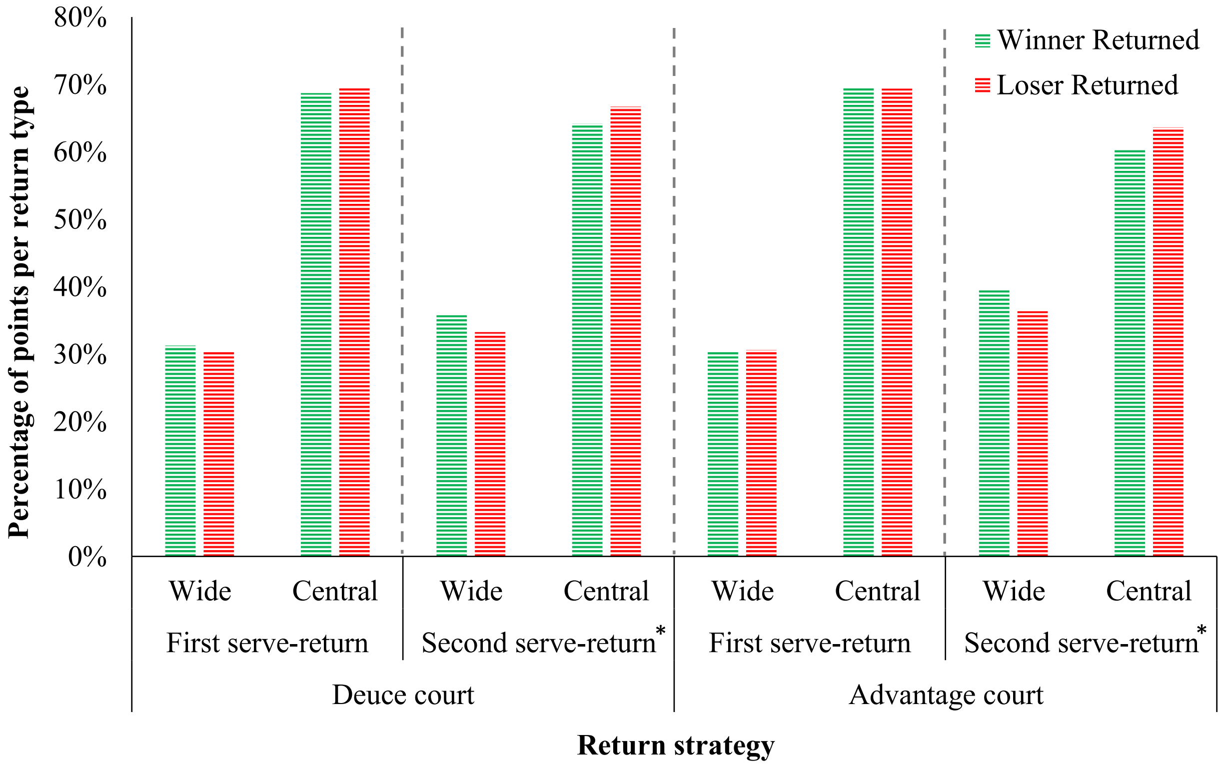


Table 9.7. shows that for all return types, female players hit more serve-returns to central zones (B and C) than wide zones (A and D), χ^2 (3, n = 11,884) = 90.56, $p < .001$, and that this difference was greater on first serve-returns than second serve-returns, χ^2 (1, n = 11,884) = 88.22, $p < .001$. For all return types, serve-returns to wide zones elicited higher success rates than serve-returns to central zones, χ^2 (3, n = 11,884) = 144.22, $p < .001$; within this, second serve-returns elicited higher success rates than first serve-returns, χ^2 (1, n = 11,884) = 143.73, $p < .001$.

9.3.5. Returning strategies executed by winning and losing players

Figure 9.4. shows, for each return type, the percentage of serve-returns executed to wide and central zones by winning and losing male players, respectively (i.e. returning strategies used by winning and losing male players).



* Return type whereby winning male players hit a higher percentage of serve-returns to wide zones than losing male players ($p < 0.05$).

Figure 9.4. *Returning strategies executed by winning and losing male players.*

Analysis revealed differences in the returning strategies executed by winning and losing male players, χ^2 (1, n = 32,594) = 6.78, $p < .01$. Winning players executed a higher percentage of second serve-returns to wide zones compared to losing players, whereas losing players executed a higher percentage of second serve-returns to central zones than winning players, deuce court: χ^2 (1, n = 7098) = 4.92, $p < .05$, advantage court: χ^2 (1, n = 6695) = 7.51, $p < .01$. No winner-loser differences were identified for first serve-return strategies.

Figure 9.5. shows, for each return type, the percentage of serve-returns executed to wide and central zones by winning and losing female players, respectively (i.e. returning strategies used by winning and losing female players).

Figure 9.5. *Returning strategies executed by winning and losing female players.*

Analysis revealed no differences in the returning strategies executed by winning and losing female players, χ^2 (1, n = 11,884) = 0.003, p > .05.

9.4. Discussion

This study aimed to identify the most prevalent and effective serving and returning strategies executed by men and women at Wimbledon, and establish associated winner-loser differences. The key findings, discussed below, enhance our understanding of the tactical strategies used by players of both sexes, and in turn, can inform players' tactical planning and preparation for the grass court season.

9.4.1. Serving strategies: prevalence and success rates (Tables 9.2. and 9.3.)

For players of both sexes, the most prevalent first serve strategies were zones A and D and the most prevalent second serve strategy was zone C, reflecting the results of Mecheri et al. (2016). Zones A and D were the most effective serving strategies, eliciting the highest success rates for serving players, for all serve types for men and women, except advantage court second serves for women. This is likely because serves to zones A and D are typically more difficult for returning players to retrieve, as they are required to move a greater distance to reach the ball, particularly when spin is applied to the serve, as the ball constantly moves further away from the returner (van de Braam & Crespo, 2014; Shelton et al., 2016). Logically, it could be expected that, if zones A and D are more successful serving strategies than zones B and C, players would execute most first and second serves to zones A and D. However, zones A and D are closer to the lateral edges of the service box than zones B and C, and are therefore more risky strategies to attempt (Ruder, 2019). Additionally, when a player misses a first serve, they can attempt a second serve (i.e. a second chance to hit a successful serve), but the consequence of missing a second serve is the immediate loss of a point (Antoun, 2007). Therefore, it is understandable that players take more risk on first serves by aiming to zones A and D more often, as they are more likely to win the point if the serve lands in, and they can attempt a second serve if they miss. On seconds serves, the high prevalence of zone C is understandable, as, despite its low success rate compared to zones A and D, it is more central and therefore safer to aim for when the consequence of missing is losing the point (Ruder, 2019). Additionally, Mecheri et al. (2016) reported that most players prefer to hit second serves to their opponent's backhand, as it is usually considered the weaker stroke; hitting a second serve to zone C means that a right-handed returner[1] is more likely to hit a backhand serve-return than a forehand serve-return. In contrast, the other central and therefore relatively safe second serve zone (zone B), is more likely to elicit a forehand serve-return, which is the preferred and stronger stroke for most elite players (Martin-Lorente et al., 2017).

9.4.2. Serving strategies executed by winning and losing players (Figures 9.2. and 9.3.)

For all serve types, winning male players hit a higher percentage of their serves to zones A and D than losing male players; correspondingly, losing players hit a higher percentage to zones B and C than winning players. As mentioned, serves to zones A and D elicited higher success rates than serves to zones B and C for men (see Table 9.2.), so the winner-loser differences revealed here are logical, demonstrating that male players who are more accurate with their first and second serves (i.e. hitting to zones A and D) more often than their opponent, typically win the match. These findings support previous assertions that the serve is an important stroke in elite tennis (Bollettieri, 2015; Mecheri et al., 2016; Klaus et al., 2017), and highlight the importance of accuracy for male players when serving on grass courts.

The same pattern was evident in the women's data for first serves, with winning players hitting a higher percentage of their first serves to zones A and D than losing players. However, for second serves, winner-loser differences were only identified in the deuce court, whereby winning female players served more second serves to zones C and D than losing players. This likely indicates that winning female players attempted to exploit their opponent's backhand

[1] Right-handed players comprised an average of 85% of men's top 100 players and 92% of women's top 100 players each year between 2015 and 2017 (ATP, 2020; WTA, 2020).

serve-return more often than losing players on deuce court second serves. However, zone C was a relatively unsuccessful strategy for deuce court second serves (see Table 9.3.), so it is not clear why it was so prevalent for women, particularly for winning players. Perhaps female players are unaware of the relatively low success rate of zone C, believing that eliciting a backhand serve-return is favourable to eliciting a forehand serve-return, which is not always the case (Antoun, 2007). Alternatively, they may be aware of it, but still prefer to execute a seemingly safer serving strategy than risk a double fault by aiming for a more lateral zone. Either way, these results suggest it may be advisable for women to spread the distribution of their deuce court second serves more. In line with this, Nigel Sears, former coach of three WTA top 10 singles players, highlighted the importance of accuracy and unpredictability of women's second serves, stating that a strong second serve keeps the opponent constantly guessing (Antoun, 2007), an observation supported by Ruder (2019).

The winner-loser differences identified in men's and women's serving strategies were small (e.g. between 1% and 4% in Figures 9.2. and 9.3.), and could therefore appear insignificant, but it is important to note that this is not the case. The outcome of a tennis match can be decided by tiny margins (O'Shannessy, 2017a); it is even possible to lose more points than an opponent in a match and still win, a phenomenon known as the Quasi-Simpson paradox (Lisi et al., 2019). This should help demonstrate how small differences between players' strategies, such as those revealed here, can influence match outcome and therefore be crucial.

9.4.3. Serve-volley strategies: prevalence and success rates (Tables 9.4. and 9.5.)

Projected values for men's serve-volley strategies appear to indicate that zones A and D were more successful than zones B and C, for all serve-volley types except advantage court second serves, where zones C and D appear to be most successful. Although no statistical analyses were undertaken, visual comparisons of the men's projected serve-volley success rates (presented in Table 9.4.) with men's overall serving strategy success rates (presented in Table 9.2.), indicate that the serve-volley success rates were typically lower than the overall success rates. Speculatively then, serve-volleying may not be a particularly successful tactic for male players, which could help explain why the tactic has become less prevalent since the 1990s (as shown in Chapter 5, Figure 5.2a). Accordingly, male players should carefully consider their approach to serve-volleying. However, as mentioned, these interpretations are speculative, and no women's serve-volley interpretations are presented, due to low sample sizes. Additionally, O'Shannessy (2017b) suggested that, in contrast to common belief, serve-volleying is undoubtedly a more successful tactic than remaining at the baseline. Further research is therefore required to investigate when and how serve-volleying strategies can be implemented most effectively during men's and women's grass court match-play. Crucially, any such research should incorporate a sufficient sample size to ensure valid conclusions.

9.4.4. Returning strategies: prevalence and success rates (Tables 9.6. and 9.7.)

In terms of returning strategies, men and women hit more serve-returns to central zones (B and C) than to wide zones (A and D) for all return types. This may be because serve-returns to central zones limit the tactical options of the server on their second shot, by reducing the space (i.e. angles) available for them to attack, making it more difficult for them to open up the court and/or finish the point quickly (Antoun, 2007; Gillet et al., 2009). The prevalence of central zones on serve-returns may also be due to the lower risk associated with these zones compared to wide zones. As with serve zones, serve-return zones A and D (i.e. wide zones) are closer to the lateral edges of the court than zones B and C, which are central and therefore less risky to target (Ruder, 2019).

Results also revealed that, for all men's and women's return types, players hit a higher percentage of serve-returns to central zones on first serve-returns than second serve-returns, and won a higher percentage of points by hitting serve-returns to wide zones than central zones. Additionally, players of both sexes won a lower percentage of points when returning first serves than when returning second serves. These results replicate those reported in Gillet et al.'s (2009) analysis of men's clay court match-play, and can be explained theoretically using ecological dynamics. From a serving perspective, an effective serve allows the server to destabilise the dynamic equilibrium of the point and gain an immediate tactical advantage (O'Donoghue & Brown, 2008). Consequently, elite players often use their serve (predominantly their first serve) as a tactical weapon to force their opponent to perform a difficult serve-return (Antoun, 2007). So, first serve-returns are typically performed in a reactive manner, with the priority of getting the ball back into play (Pretorius & Boucek, 2020). Under these extreme constraints, first serve-returns are less likely to trouble the server, and often leave the returner at a tactical disadvantage in the point; partly explaining why players won a lower percentage of first serve-return points than second serve-return points. Additionally, if the primary goal on first serve-returns is simply to hit the ball back into court, rather than attempting to hit a winner or force the server to commit an error, which is considered difficult and risky (Bollettieri, 2015), then central zones are the safest to target. This may be why players executed a higher percentage of first serve-returns to central zones than second serve-returns.

The higher success rates achieved by players returning second serves compared to returning first serves and the higher percentage of strokes hit to wide zones on second serve-returns compared to first serve-returns could also be explained by the tendency for elite players to opt for a faster first serve, slower second serve strategy (Barnett et al., 2008; Pollard, 2008). Slower second serves are hit more conservatively than first serves (Antoun, 2007), so, from a returning perspective, second serves afford the returner more time to prepare for their stroke (Gillet et al., 2009). Therefore, on second serve-returns, as proposed in Chapter 8, players are more likely to be able to be position themselves optimally to execute an attacking and accurate serve-return to a wide zone, placing time and positional constraints on the serving player, and potentially creating a perturbation that could lead to the returning player winning the point. In contrast, faster first serves impose greater time constraints on the returning player, restricting the time available to react and perform a serve-return, resulting in a higher likelihood of the serving player winning the point.

9.4.5. Returning strategies executed by winning and losing players (Figures 9.4. and 9.5.)

In terms of winner-loser differences in returning strategies, winning male players hit a higher percentage of second serve-returns to wide zones than losing male players. This indicates that winning male players were able to recognise and exploit their opponent's weaker second serves, executing accurate serve-returns to wide zones, more often than losing players. In turn, this immediately exposes the server to positional constraints, affording the returner the tactical advantage early in the point. This winner-loser difference supports the assertion that players who can use their opponent's weak second serve to their own advantage have a major asset in their arsenal (Gilbert & Jamison, 2013).

No winner-loser differences were identified for women's returning strategies, or for men's first serve-returns. This could imply that returning strategies are not important for women, and are only somewhat important for men, but earlier work in this thesis demonstrated the critical importance of the serve-return for winning matches in elite grass court tennis (see Chapter 8). So, it is possible that other factors or combinations of factors linked to the serve-return, rather than accuracy (i.e. zone), differentiate winning and losing players; these could include serve-return speed, serve-return spin (Gillet et al., 2009), and/or more specific serve-return accuracy measures than those analysed in this study.

9.4.6. Limitations

Within the current dataset, all stroke errors were recorded as having three-dimensional coordinates of (0,0,0), so it was not possible to establish ball landing locations for missed strokes (i.e. those that landed in the net, wide of the sideline or behind the baseline), or infer any intended strategy. Accordingly, contextual understanding is paramount to the appropriate interpretation of the results presented here. Additionally, only one indicator of strategy – ball landing location – was analysed. Despite having been shown to influence the probability of winning a point (Gillet et al., 2009), ball speed and ball spin rate were not measured. These limitations are addressed in the context of future research in the Epilogue (Chapter 10). Finally, future serve and serve-return related studies should aim to stratify data by handedness, as serving strategy has been shown to differ between left- and right-handed players (Loffing et al., 2009).

9.5. Conclusion

This study has provided new insights into the serving and returning strategies executed in elite grass court tennis. Male and female players preferred to hit first serves to the lateral edges of the service box, putting their opponent under time and positional pressure. On second serves, players typically opted for a safer strategy, while potentially trying to elicit a backhand serve-return. Central zones were the most common returning strategies for both sexes, particularly on first serve-returns, possibly because these zones present less risk than wide zones. Despite this, wide zones elicited more success for returning players than central zones, particularly on second serve-returns, likely due to the additional time afforded to returning players to prepare for their stroke, compared to first serve-returns. Male winning players forced their opponents into difficult positions more often than losing male players, hitting a comparatively higher percentage of their serves and serve-returns to lateral areas; female winning players demonstrated this behaviour only on first serves. These results contribute to a growing body of research analysing Hawk-Eye's ball-tracking data in elite tennis, and provide greater context around the results presented earlier in this thesis, enhancing our understanding of how matches are won at Wimbledon. Discussed further in the Epilogue (Chapter 10), coaches can use these findings to improve the representative design of players' grass court training, ensuring practices are sufficiently reflective of match-play, and to inform players' tactical preparation.

Chapter 10

Epilogue

10.1. Advancing knowledge

The studies in this thesis have helped to address the paucity of notational analysis research investigating elite grass court tennis. In addition to introducing and validating a novel data analysis method (Chapter 3), the findings advance knowledge on the important aspects of grass court tennis match-play and provide new insight into how matches are won at Wimbledon. Longitudinal analysis highlighted that although the performance characteristics of match-play changed between 1992 and 2017, short points remained the most important characteristic throughout (Chapter 5). Informed by practitioners' experiential knowledge, operational definitions for *closely contested* and *one-sided* tennis matches were developed (Chapter 6), and can be used in future studies to stratify data by match closeness. The first investigation of elite tennis match-play from the perspective of match closeness revealed that short points were highly important in both *closely contested* and *one-sided* matches (Chapter 6). The findings also enhance our understanding of the player-environment interaction, with regards to the clay-to-grass court surface transition between Roland Garros and Wimbledon (Chapter 7). An examination of short points indicated that serve plus one strategies do not differentiate winning and losing players (Chapter 8); and tactical analysis provided new insight into the most common and most effective serving and returning strategies for elite players at Wimbledon (Chapter 9).

The contextual interpretation of results presented throughout this thesis can inform coaches aiming to develop evidence-based practices and ensure grass court training is representative of match-play. Designed to inform future practice, the practical applications explored below, pertain to four key areas; implications for coaches, implications for performance analysts, implications for high-performance centres, and future directions for research.

10.2. Implications for coaches: representative practice design

Findings revealed that *points won of 0-4 shot rally length* (i.e. short points) was the most important performance characteristic in terms of winning matches at Wimbledon, irrespective of sex, time (Chapter 5) and match closeness (Chapter 6). Coaches should be aware of the prevalence and importance of short points, and design players' training accordingly. Guided by Pinder et al.'s (2011) representative learning design framework, coaches should ensure that short rallies and point-ending strategies are fundamental aspects of players' grass court training sessions. However, the ATP Tour Strategy Analyst, Craig O'Shannessy, recently suggested that elite players spend around 90% of their practice time engaging in long, baseline rallies (O'Shannessy, 2019d). This type of practice develops rhythm and consistency (Giampaolo & Levey, 2013), and should therefore not be abandoned, but the importance of providing a training environment that is representative of the performance context should not be overlooked. The findings in this thesis therefore suggest that the amount of time spent practicing long baseline rallies should be reconsidered and potentially reduced, due to the prevalence and unconditional importance of short points (Chapters 5, 6 and 7). Additionally, informed by these findings, coaches can be guided on how to design more representative baseline rallies, to ensure high levels of specificity within players' training; strategies for this are presented shortly.

Chapter 8 highlighted the crucial role of serving and returning strategies at Wimbledon. According to O'Shannessy (2020), the serve and particularly the serve-return are drastically under-practised skills, relative to their prevalence in elite level match-play. Although this has not yet been investigated empirically in professional tennis, Krause et al. (2019) analysed junior players' training sessions and demonstrated that serves and serve-returns comprise only 10% and 3% of total practice time, respectively. With findings in Chapter 8 demonstrating that serving and returning strategies are highly influential to the outcome of matches, serves and serve-returns should undoubtedly be afforded attention during grass court training. Findings indicated that, for male players, serve-returns may be more important than serves, so it is particularly important for men's coaches to ensure serve-returns are afforded sufficient practice time. Currently, players tend to practise the serve by repeatedly hitting balls from a basket, engaging in conversation simultaneously (Meffert et al., 2018) and without a returning player present (Krause et al., 2019); it is important to address the representativeness of such practice designs (Van Aken, 2002). To more accurately represent the performance context, serves and serve-returns should not be practised in isolation, but rather as they occur during match-play – as part of a series of strokes, beginning with a first or second serve (Krause et al., 2019; O'Shannessy, 2019d). Therefore, serving practices in which players are dissuaded from talking, a returning 'opponent' is active, and the serving player is required to perform the next stroke if the serve-return is successful, are advised.

Points won of 3 shots did not differentiate winning and losing players (Chapter 8), casting doubt on claims that serve plus one strategies are crucial in elite tennis (e.g. Anderson, 2018b; Palmer, 2019; O'Shannessy, 2019c). However, this finding must be considered in context; *3 shots* was the second most common rally length, and changing the amount of practice time afforded to serve plus one strategies could lead to players becoming less proficient at executing them. So, it would be imprudent to suggest that serve plus one strategies should not be practised, but coaches could ensure specificity, affording time to the specific strategies that their player executes either more or less successfully in match-play.

Serves and serve-returns landing close to the lateral edges of the court were more successful than those landing in central zones (Chapter 9). The importance of short points, the importance of serving and returning strategies, and the success of serving and returning to lateral zones (compared to central zones) collectively indicate that success is typically attained at Wimbledon by executing attacking strategies that put the opponent under pressure early in the point. In line with these results, coaches should design practices that elicit proactive behaviours and foster attacking strategies, such as playing on the front foot, stepping inside the baseline, taking the ball early (i.e. on the rise), and putting the opponent under positional and/or time pressure.

Newell's (1986) constraints-led model is an effective pedagogical approach for promoting desirable emergent behaviours (Renshaw & Chow, 2019), and can therefore underpin coaches' development of such practice designs. Below are four task designs that coaches could explore, whereby constraints are manipulated to encourage functional behaviours. These suggestions are informed by the findings in this thesis and derived from tennis coaching literature.

1. *Time-restricted rallies*

   Players rally for 60 seconds, with the aim of hitting as many strokes as possible (ideally within one rally). As players explore behavioural adaptations to achieve the goal (Davids, 2010), they learn to reduce the amount of time between strokes, and therefore hit more strokes within the time limit, by taking the ball early and executing an attacking ball trajectory. Time-constrained tasks can also improve players' capacity to play at a high tempo while maintaining consistency, a vital skill in tennis (Antoun, 2007). Informed by the finding that short points are closely associated with success (Chapters 5, 6 and 7), this task will encourage players to put their opponent under time pressure early in the point.

2. *Adapted playing space* (Hopper, 2011; Fitzpatrick et al., 2018)

   Use masking tape or markers to create a line 10 cm behind the baseline, demarcating the effective playing space that players must stay within. Under this adaptation, incoming balls that land near the baseline must be taken on the rise to satisfy the task demands. Over time, players learn that this imposes time pressure on the opponent. During points-based activities, this manipulation ensures that players do not retreat after serving, in turn promoting active consideration of an appropriate serving strategy. This task is informed by the importance of serving strategies (Chapter 8), and the finding that winning players hit a higher proportion of their serves to wide zones than losing players (Chapter 9).

3. *Two steps forward*

   During serve-return tasks, ask players to take two steps forward after each stroke. This promotes hitting on the front foot and moving through the ball, and fosters an attacking mentality, as it is difficult to play defensively when moving forwards. With the importance of returning strategies (particularly for men, Chapter 9), this will encourage players to attack the serve-return in order to prevent the server from dominating the start of the point. This manipulation can also be used during baseline rallies to improve players' forward and backward movement skills, which are typically weaker than their lateral movement skills (Campbell, 2020).

4. *Bonus points for creating perturbations* (Fitzpatrick at el., 2018)

   Coaches can award a bonus point if players miss by a small margin while attempting to create a perturbation (i.e. apply time or positional pressure) early in the point, to promote positive intent. Informed by the importance of short points (Chapters 5, 6 and 7), this task fosters an attacking (rather than passive or defensive) approach to the first few strokes of each point, by negating the psychological pressure associated with committing an error. Bonus and/or penalty points can be applied to many activities, to promote desirable behaviours or dissuade less-desirable behaviours.

Relevant verbal instruction and feedback (i.e. clear and simple statements) should be provided by coaches to supplement these manipulations (Reilly & Williams, 2003; Lavallee et al., 2012).

Examples that reflect the findings of this thesis include 'hit through the ball', 'take their time away' or 'strike first' to encourage proactive play (Ruder, 2019). Where possible, practice environments should also elicit the cognitions and emotions associated with competition, to better support the emergence of functional behaviours and exhibit fidelity with the performance context (McCosker et al., 2019). Coaches can aim to re-create the high-pressure environment of competition using forfeits and rewards (Stoker, 2017), or by implementing time restrictions and/or situational scoring manipulations (e.g. the player must start each game 0-30 down) (Pinder et al., 2015). As tennis is an individual sport, putting players into teams, whereby everyone's performance affects the success of the team may also simulate pressure.

For the successful implementation of practice designs, players must understand the purpose, relevance and context, to ensure they adopt an appropriate mindset (Ruder, 2019). Based on present findings (the importance of *points won of 1 shot*, *points won of 2 shots*, *points won of 4 shots*, and the importance of serving and returning strategies for winning matches at Wimbledon, Chapter 8), players should approach practice prepared to actively search for and create opportunities to win the point, rather than passively waiting for opportunities to arise or for their opponent to commit an error. To facilitate this mentality, coaches could ask players to verbalise their tactical intention as they perform each stroke, by calling out 'defend', 'neutral', or 'attack'. Self-evaluation, an important skill for athletes (Schunk & Zimmerman, 2011), has been shown to improve focus, and enhance particularly those areas within players' control, such as the serve (Taylor & Wilson, 2005). Self-assessing the effectiveness of serves and serve-returns during training, by scoring them out of ten, based on how difficult the player perceives each stroke to be for an opponent to retrieve, could encourage exploration of different ways to execute serves and serve-returns to increase the likelihood of creating a perturbation.

Crucially, the coaching application outlined is not 'one size fits all', and must be individualised (Meyers, 2006). Given the array of game styles in tennis, and players' individual personalities, coaches have a responsibility to know their own player's game and character well enough to determine how, and the extent to which, they should implement these recommendations with them (Reilly & Williams, 2003). In this way, the tactical strategies of an individual player should maximise their strengths, while limiting the opportunities for opponents to exploit their weaknesses. (Antoun, 2007). How coaches communicate the context of findings and associated adaptations is also important (Launder, 2001; Jones et al., 2004). For example, with a male player whose weapon is their powerful serve, a coach may highlight the strengths of this game style on grass courts, based on the critical importance of serving revealed in Chapter 8 and the importance of *first serve speed* and *aces* uncovered in Chapter 5, to instil confidence and self-belief (Wilkins & McBrien, 2018). However, for a player whose strengths are movement and shot consistency, expressing that their game style is not ideal for grass courts, as long points are not important for winning matches at Wimbledon (Chapters 5 and 6) is unlikely to be beneficial. So, coaches must consider players' gamestyles and personalities before deciding how best to design sessions and explain adaptations.

10.3. Implications for performance analysts

Performance analysts can only function optimally within an elite sport setting if coaches and players understand their purpose (Meyers, 2006; Carling et al., 2008). As highlighted in the Literature Review (Chapter 2), tennis coaches have resisted performance analysis, struggling to comprehend its relevance (Briggs, 2018). Additionally, the researcher's first-hand experience has highlighted that some players are interested in performance data, but are discouraged from engaging with analysts, with all communication filtered through the coach. The practitioner friendly PWOL method is easy to calculate, interpret and contextualise, and can therefore be adopted by analysts, particularly when liaising with coaches to improve their engagement with performance data. Furthermore, if the method enhances coaches' understanding, they may facilitate more direct communication between analysts and players. PWOL is also a research-informed tool that can support efficient working practices, by helping analysts to filter the range of performance characteristics they analyse.

To optimise the application of performance data, the effective presentation and efficient communication of findings is essential (Hughes et al., 2019). Rather than presenting complex, graphical displays to coaches, as has often been the case (Meyers, 2006), analysts should complement their quantitative work with concise, contextual interpretation (Martinez Arastey, 2020). In this context, 'dense academic language' has been cited by coaches as a key barrier that leads to poor understanding and negative perceptions of scientific disciplines (Renshaw & Chow, 2019), emphasising the need for more appropriate 'lay' language when reporting scientific findings (Williams & Kendall, 2007). It can be particularly difficult for analysts with limited tennis experience to articulate findings effectively. By producing percentage values, the PWOL method could facilitate communication between analysts and coaches, negating the need for academic terms such as 'significant difference' and 'correlation', for example. Further recommendations are provided in Section 10.4.3. to support analysts in this regard.

10.4. Implications for high-performance centres

For the current findings to be successfully applied within elite tennis environments, several aspects should be addressed. To complement and support the direct practical applications of the work in this thesis, presented above (i.e. implications for coaches and implications for performance analysts), this section explores the wider but important challenge of enhancing the application of performance analysis findings in high-performance environments.

Commentary on current practices within high-performance centres and suggestions to improve these are also provided, based on literature and the researcher's experiential knowledge.

10.4.1. Developing a culture

It is widely acknowledged that an effective culture is at the centre of most successful organisations (Jackson, 2016). An organisation's culture can be considered as the behaviours promoted and accepted, and is characterised by the thoughts and actions of its members (Young, 2020). A strong culture can elicit multiple benefits within sporting organisations, including facilitating communication and cooperation, promoting unity, and supporting shared beliefs and values (Lussier & Kimball, 2019).

The researcher's experience as a professional player with Monte Carlo Tennis Academy (MCTA) should highlight further benefits of a strong culture. Inspired by a Grand Slam Champion, the MCTA players adopted the philosophy 'no ball will bounce twice', and committed to consistently demonstrating this belief; a simple mantra of 'run' complemented the philosophy. While the notion of never letting a ball bounce twice was unrealistic, it encouraged players to chase every ball, no matter how unlikely it was that they would retrieve it. The MCTA conditioning coach designed practices to improve players' speed and endurance, which further embedded the philosophy. The emergent culture gave players a competitive edge; as they began to retrieve balls that others would dismiss as 'lost causes', fellow competitors saw the culture borne out on the match court, knowing that an MCTA player would run for every ball, and always had a chance of turning a match around.

A proposed benefit of a *research-informed* culture is the inherently dynamic nature; as new research emerges, the organisation's culture can evolve accordingly, which prevents the common pitfall of cultural stagnation (Lussier & Kimball, 2019). Aligned with the findings of this thesis, an appropriate culture for high-performance centres to develop could be one in which attacking play and calculated risks are consistently encouraged and rewarded, and unforced errors are not criticised. Incorporating constraints-led practices such as those presented previously (see Section 10.2.1.) would support this.

10.4.2. Structural redesign

Evidence suggests that the typical structure of tennis high-performance centres does not facilitate the application of performance analysts' work (and likely that of other sport scientists). In line with reports in the literature of 'gaps' between sport scientists and coaches (Carling et al., 2008; Greenwood et al., 2014), current high-performance models tend to consist of isolated specialists working 'in silos' (Springham et al., 2018). This fragmented approach leads to poor working dynamics and performance outcomes (Hristovski et al., 2017; Rothwell et al., 2020). To ameliorate the issue, Rothwell et al. (2020) proposed a 'Department of Methodology', a space shared by coaches and applied sport scientists, in which experiential and empirical knowledge can be effectively integrated to enrich the application and working practices of both.

While the rationale for creating such a department is sound, solutions must not exacerbate existing issues. As 'dense academic language' has contributed to coaches' negative perceptions of sport science (Renshaw & Chow, 2019), and previous research has highlighted a need for more appropriate 'lay' language (Williams & Kendall, 2007), a redesign of current structures may be preferable. Accordingly, consolidating the sport science department and the coaching department in high-performance centres into a single, concisely named 'Performance Support' department (occupying a shared physical workspace), is suggested, alongside the unequivocal adoption of a universal, sport-specific language. The term 'Performance Support' negates any ambiguity around the department's purpose and, with a proposed aim of improving the functionality and interdisciplinarity of the currently disparate disciplines, these changes would promote collaboration, innovation and highly effective integration (Rothwell et al., 2020), as well as conveying a cohesive approach to player development.

10.4.3. Targeted recruitment and development opportunities

The experiential knowledge of coaches and players is a critical source of information and evidence (Woods et al., 2021), but often, its role and value have been overlooked within sport science departments (Rothwell et al., 2020), with empirical knowledge treated as the sole source of evidence to inform practice (Woods et al. 2021). However, sport-specific experience is invaluable for gaining the respect of players and coaching staff and facilitating open communication (Jones et al., 2004). Contemporary research has demonstrated how a combination of experiential and empirical knowledge can enrich research, application and practice in elite sport (Rothwell et al., 2020). In this context, shrewd recruitment and pertinent continuing professional development (CPD) could help ameliorate the current disconnect between performance analysts and coaches. For example, when recruiting, high-performance centres could consider canvassing former players, and providing them with opportunities to train as analysts. Their experiential knowledge would enable them to effectively build rapport with coaches and players, while developing empirical knowledge and an applied scientific skillset.

For the work of sport scientists to become fully integrated into elite player development programmes, sport scientists must better understand the needs of players and coaches, and, correspondingly, coaches must improve their understanding of sport science (Carling et al., 2008). Only then can theoretical principles be effectively implemented to enhance performance. Accordingly, high-performance centres should consider educating coaches to enhance their understanding of basic scientific principles and theoretical concepts, to facilitate their relationships with sport scientists. Additionally, high-performance centres should seek to upskill current analysts, who have empirical knowledge, by integrating them into the performance environment and facilitating more interactions with players and coaches, to improve their contextual understanding. Immersing analysts this way would expedite their familiarisation with tennis-specific language, allowing them to communicate more effectively with players and coaches.

10.4.4. Player engagement

Contemporary research has suggested that elite athlete development models would be enhanced if athletes were actively engaged in the learning process (Woods et al., 2021). Involving athletes in discussions around their own development could empower them to take ownership of their learning (Morgan & Hassan, 2015), promote a deeper understanding of their expertise domain (Siedentop et al., 2019), and augment their contextual intelligence (Woods et al., 2021). Furthermore, elite athletes offer a wealth of experiential knowledge, different from that of coaches, which is rarely explored within current athlete development models (Woods et al., 2021). Therefore, rather than discouraging players from communicating with performance analysts, actively engaging them in their own development and inviting their input is advised. Importantly, this pedagogical approach would intrinsically educate players around the scientific principles that underpin player development, in a way that would facilitate their future involvement as interdisciplinary performance support staff.

It is proposed that exploring these suggestions would progress high-performance centres towards a working practice, whereby performance support departments draw upon empirical and experiential knowledge to guide the integration of theory into coaching practice (Greenwood et al., 2012). In this way, programmes would be underpinned by rigorous theoretical concepts, and brought to life with rich context based on the 'lived experience' of coaches and players (Woods et al., 2021).

10.5. Future directions for research

To build on the work in this thesis, future studies analysing aspects such as ball impact location, ball speed and ball spin rate are recommended, to help develop a more holistic understanding of serving and returning strategies and associated winner-loser differences. With more sophisticated methods of performance tracking, such as Hawk-Eye technology, now commonplace in elite tennis (Reid et al., 2016), performance characteristics not typically reported (e.g. ball landing location, distance travelled, average movement speed) could become more accessible. Future work should investigate the potential use of the PWOL method for these new (and currently under-used) performance characteristics. Additionally, future research should seek to record accurate ball landing coordinates of missed strokes. This would enable the calculation of strategy conversion rates and other related metrics; for example, the number of times players executed a particular serving strategy and won the point as a percentage of the total number of times they attempted to execute that strategy. To complement the grass court research undertaken here and the hard court research undertaken by Reid et al. (2016), Hawk-Eye data from clay court match-play should be investigated, to facilitate surface comparisons and provide greater context around the clay-to-grass and hard-to-clay court surface transitions. Research investigating elite players' current grass court training practices is also recommended, potentially adopting a case study approach, to establish the extent to which current practices reflect match-play. This would ideally comprise an intervention study, with constraint-based manipulations, such as those presented in this chapter, employed to enhance the representative design of players' training. Finally, research exploring the application of performance analysis findings within elite tennis, and how the process can be optimised in high-performance environments is recommended.

10.6. Summary

In conclusion of this thesis, the following points summarise the wide-ranging practical applications of the work presented:

- Based on current findings, coaches should design practices that elicit proactive behaviours and foster attacking strategies (e.g. playing on the front foot, taking the ball early, and putting the opponent under positional and/or time pressure).
- To reflect match-play, coaches should develop representative and specific serve, serve-return and serve plus one based practices, and consider the amount of time players spend engaging in long, baseline rallies.
- The four constraints-led task designs presented demonstrate how coaches can apply the current findings, with appropriate instruction and feedback, to ensure representative practice.
- Coaches should tailor the implementation of such task designs, based on individual players' game styles and characters.
- Adopting the PWOL method could facilitate performance analysts' interactions with coaches, and improve coaches' engagement with performance data.
- Findings could be applied in a wider context to develop a research-informed culture in high-performance centres.
- High-performance centres could consider merging their coaching department and sport science department into a single 'Performance Support' department, to share contextual language, promote collaboration and integration, and facilitate the holistic application of scientific disciplines to improve performance.
- Targeted recruitment and pertinent development opportunities would support this.

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Appendix A

Wimbledon tennis terminology definitions

The following paper provides a definition of key statistics and terms used by IBM at Wimbledon. The objective is to avoid potential misunderstandings of various commonly used tennis terms.

Serve-related terms and statistics

Serve: The shot that starts a point.

Successful first serve: a first serve that travels over the net and lands inside the designated service box.

Successful first serves %: The number of successful first serves, as a proportion of the total number of first serve attempts.

Ace: A serve that was judged to be in play, which the receiver failed to touch with his racket. A serve that touches the receiver's body, but has not touched the receiver's racket, is defined as an Ace.

Aces %: The number of aces as a proportion of the total number of serves attempted.

Double Fault: A second serve fault.

Double faults %: The number of double faults committed as a proportion of the total number of serve points.

Serve Point: A point played when serving.

Serve Points Won %:
First - The number of first serve points won as a proportion of the total number of successful first serves.
Second - The number of second serve points won as a proportion of the total number of second serves attempted.

Serve-return related terms and statistics

Serve-Return: A return of serve, from either the forehand or backhand.

Serve-Return Point: A point played when the opponent is serving.

Serve-Return Points Won %:
First - The number of first serve-return points won as a proportion of the total number of first serve-return points played.
Second - The number of second serve-return points won as a proportion of the total number of second serve-return points played.

Baseline-play related terms and statistics

Forehand: A shot (groundstroke) whereby the palm of the hand faces the direction in which the player aims to hit the ball.

Backhand: A shot (groundstroke) whereby the back of the hand faces the direction in which the player aims to hit the ball.

Baseline Shot: Forehand or backhand groundstrokes generally played from at or near the baseline and behind the service line, to include drive volleys hit from near the baseline.

Baseline Point: A point in which the player is at or near the baseline at the time the outcome of the point was determined.

Baseline Points Played %: The number of baseline points played as a proportion of the total number of points played.

Baseline Points Won %: The number of baseline points won as a proportion of the total number of baseline points played.

Net-play related terms and statistics

Serve-Volley Point: When a server immediately approaches the net after delivering the serve, irrespective of whether or not a volley was actually made.

Serve-Volley Points Played %: The number of serve-volley points played as a proportion of the total number of serve points.

Serve-Volley Points Won %: The number of serve-volley points won as a proportion of the total number of serve-volley points played.

Net Play: Any shot hit from at or near the net, to include volleys, half-volleys, smashes or other strokes at net that are hit within the forecourt. Net Play includes strokes from within the forecourt or while the player is approaching the net which is hit prior to bouncing or at the moment of bouncing, to include half-volleys, drop volleys and lob volleys.

Net-Play Point: A point in which the player is at or near the net at the time the outcome of the point was determined.

Net-Play Points Played %: The number of net points played as a proportion of the total number of points played.

Net-Play Points Won %: The number of net-play points won as a proportion of the total number of net-play points played.

Point-ending related terms and statistics

Winner: A stroke hit during a rally whereby the opponent failed to touch the ball.

Unforced Error: When a player fails to maintain a rally or return a serve and is not judged to be under physical pressure as a result of the placement, power or spin of the opponent's stroke. Double faults are also classified as unforced errors. Because careful judgement is required on service returns the following guidelines are used:

Men's First Serve. It is probable that all return errors would be forced and it is only by exception that a serve would be weak enough to classify an error as unforced.

Men's Second Serve. Careful consideration is given to the quality and forcefulness of the serve. Strong servers, on grass, will generate some forced errors on their second serves, but weaker second serves that are not forceful will classify returns as unforced.

Women's First Serve. The majority of return errors will be classified as forced, but for those players without aggressive serves there will be occasions when a return would be judged as unforced.

Women's Second Serve. The majority of return errors are likely to be unforced, but by exception there will be some aggressive serves where the appropriate judgement is a forced error.

Forced Error: Any error during a rally or on a serve-return that is not defined as unforced.

N.B. Unforced errors and forced errors require judgement in recording by the data entry operators.

Winners %: The number of winners as a proportion of the total number of winners, unforced errors and forced errors combined.

Unforced Errors %: The number of unforced errors as a proportion of the total number of winners, unforced errors and forced errors combined.

Forced Errors %: The number of forced errors as a proportion of the total number of winners, unforced errors and forced errors combined.

Forehand Winners %: The number of forehand winners as a proportion of the total number of forehand winners and backhand winners combined.

Backhand Winners %: The number of backhand winners as a proportion of the total number of forehand winners and backhand winners combined.

The respective definitions of Forehand Unforced Errors %, Backhand Unforced Errors %, Forehand Forced Errors % and Backhand Forced Errors % replicate the above definitions of Forehand Winners % and Backhand Winners %.

Rally lengths related terms and statistics

Rally length: The number of successful strokes (i.e. strokes whereby the ball crosses the net, to the side of the opponent, and lands inside the court) during a point; errors are not counted in the rally length of a point.

Points Played of 0-4 Shot Rally Length %: The number of points with a rally length of between 0 and 4 strokes as a proportion of the total number of points played.

Points Won of 0-4 Shot Rally Length %: The number of points won of 0-4 shot rally length as a proportion of the total number of points played of 0-4 shot rally length.

The respective definitions of Points Played of 5-8 Shot Rally Length %, Points Won of 5-8 Shot Rally Length %, Points Played of 9+ Shot Rally Length %, Points Won of 9+ Shot Rally Length % replicate the above definitions for Points Played of 0-4 Shot Rally Length % and Points Won of 0-4 Shot Rally Length %.

Break point related terms and statistics

Break Point: A point with a scoreline that presents an opportunity for the returning player to win the opponent's service game.

Break Points Won %: The number of break points won as a proportion of the number of break points played.

Appendix B

Post-hoc results and Cohen's *d* effect sizes (Chapter 8)

Cohen's *d* effect sizes are defined as follows: ≥ 0.2 is small, ≥ 0.5 is medium, ≥ 0.8 is large (Cohen, 1988).

Men

Post-hoc testing showed that, for men, a rally length of *1 shot* (76.3 ± 29.6) was more common than rally lengths of *0 shots* (7.5 ± 3.8) ($p < 0.001$, $d = 3.26$), *2 shots* (25.4 ± 9.6) ($p < 0.001$, $d = 2.31$), *3 shots* (36.3 ± 13.2) ($p < 0.001$, $d = 1.75$) and *4 shots* (17.7 ± 6.1) ($p < 0.001$, $d = 2.74$). Additionally, a rally length of *3 shots* (36.3 ± 13.2) was more common than rally lengths of *0 shots* (7.5 ± 3.8) ($p < 0.001$, $d = 2.96$), *2 shots* (25.4 ± 9.6) ($p < 0.001$, $d = 0.94$) and *4 shots* (17.7 ± 6.1) ($p < 0.001$, $d = 1.81$). A rally length of *2 shots* (25.4 ± 9.6) was more common than rally lengths of *0 shots* (7.5 ± 3.8) ($p < 0.001$, $d = 2.46$) and *4 shots* (17.7 ± 6.1) ($p < 0.001$, $d = 0.97$), and in turn, a rally length of *4 shots* (17.7 ± 6.1) was more common than a rally length of *0 shots* (7.5 ± 3.8) ($p < 0.001$, $d = 1.99$).

Women

Post-hoc testing showed that, for women, a rally length of *1 shot* (34.4 ± 13.2) was more common than rally lengths of *0 shots* (6.2 ± 3.5) ($p < 0.001$, $d = 2.91$), *2 shots* (19.1 ± 7.4) ($p < 0.001$, $d = 1.43$), *3 shots* (20.9 ± 7.9) ($p < 0.001$, $d = 1.24$) and *4 shots* (13.5 ± 5.7) ($p < 0.001$, $d = 2.05$). Additionally, a rally length of *3 shots* (20.9 ± 7.9) was more common than rally lengths of *0 shots* (6.2 ± 3.5) ($p < 0.001$, $d = 2.39$), *2 shots* (19.1 ± 7.4) ($p < 0.01$, $d = 0.24$) and *4 shots* (13.5 ± 5.7) ($p < 0.001$, $d = 1.07$). A rally length of *2 shots* (19.1 ± 7.4) was more common than rally lengths of *0 shots* (6.2 ± 3.5) ($p < 0.001$, $d = 2.21$) and *4 shots* (13.5 ± 5.7) ($p < 0.001$, $d = 0.84$), and in turn, a rally length of *4 shots* (13.5 ± 5.7) was more common than a rally length of *0 shots* (6.2 ± 3.5) ($p < 0.001$, $d = 1.55$).