Pace and variability in the badminton jump smash and the tennis serve

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By

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ABSTRACT

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Full-body three-dimensional kinematic characteristics were determined for the badminton jump smash and the tennis serve in order to investigate contributions to pace and variability. Kinematic (400 Hz) data were collected for a group of badminton and tennis players, using an 18 camera Vicon Motion Analysis System. Each participant performed 24 jump smashes or tennis serves. The best trials - maximal velocity with minimal marker loss - were analysed for each participant using a 18 segment rigid body model customised for each participant using subject-specific segmental properties. Parameters were calculated describing elements of the badminton jump smash and tennis serve technique as well as variability. The effect of these technique parameters on: speed were addressed using stepwise linear regression and on variability using one-way ANOVA. The results suggest that the fastest badminton players had a smaller elbow extension angle at the end of retraction, a larger wrist extension angle at shuttle contact, and a larger time between preparation and shuttle contact; that accounted for 84% of variation in shuttle speed. The results also showed that variability in the badminton smash was caused by differences in body placement, shuttle location on the racket at impact and movement timings. In the tennis serve, linear regressions showed that there were no variables significant to speed when players hit to the right and left centre court lines. When players hit in the advantage court trunk rotation at the racket lowest point key instant could explain 35.2% of the variation in speed, and when hitting towards the deuce court timing from the end of retraction to ball contact explained 33.6% of ball speed. The results show that there are differences in technique between the badminton jump smash and the tennis serves especially in the first half of the sporting actions.

PUBLICATIONS

Conference Presentations:

Miller, R., King, M.A., 2014. A Biomechanical Analysis of Racket Sports: A look at speed and accuracy in tennis serve and badminton smash. SSEHS Postgraduate Research Conference, Loughborough University.

Miller, R., Felton, P., McErlain-Naylor, S., Towler, H., King, M.A. Relationship between technique and velocity in the badminton jump smash., 2015. *Proceedings of the 14th ITTF Sports Science Congress and 5th World Racquet Sports Congress, Suzhou*.

McErlain-Naylor, S., Miller, R., King, M.A., Yeadon, M.R., 2015. Determining instantaneous shuttlecock velocity: Overcoming the effects of a low ballistic coefficient. *Proceedings of the 14th ITTF Sports Science Congress and 5th World Racquet Sports Congress, Suzhou*.

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DEDICATION

I would like to dedicate this to my brother who passed away from cancer. Although he is not here physically his spirit and love surround me daily.

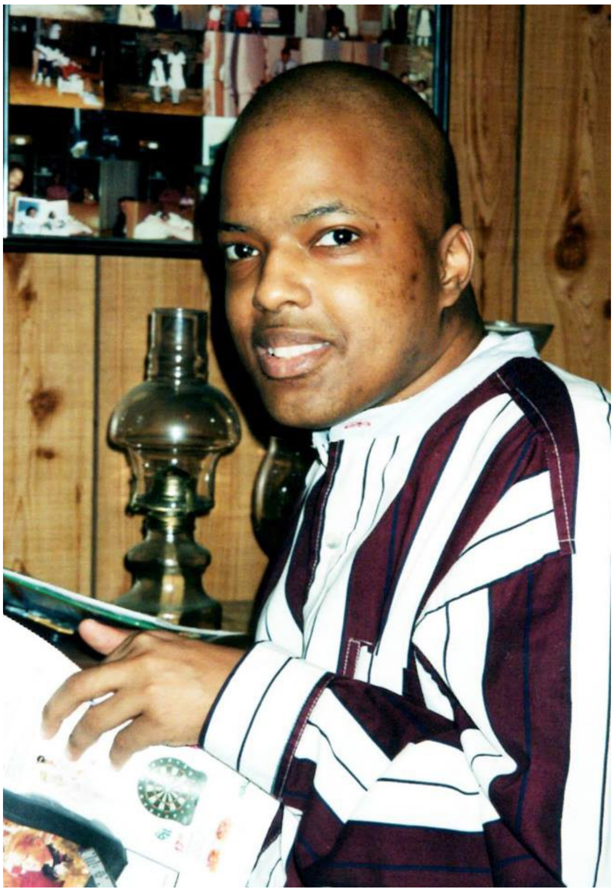


Table of Contents

List of Figures

Table of Tables

CHAPTER 1: INTRODUCTION

This chapter provides details of the motivation for this thesis and an outline of the previous research conducted in this area. The purpose of the study is explained and research questions are posed with reference to the literature. Lastly, an overview of this thesis is provided with a brief description of each chapter.

1.1 The Area of Study

Two of the major racket sports in the world are badminton and tennis. In 2013 it was estimated that over 250 million people play badminton worldwide. It is also estimated that over 1.2 billon people either play or watch tennis. Overarm movements are essential skills in these sporting games. The growth of racket sports has led to focused attention on improved performance and detailed study and understanding of all aspects of racket sports. The tennis serve and badminton smash are used to induce pressure on the opposing player to score points (Figure 1.1; Wagner et al., 2012).

The badminton jump smash is the most aggressive stroke in badminton. The smash is thought to be an important means of getting points to win a game (Sakurai and Ohtsuki, 2000).

Like the badminton smash, the tennis serve is one of the most effective weapons a player has during a match. The tennis serve is the most complex stroke in competitive tennis. The tennis serve can be a big factor in winning a game for a player (Kovacs and Ellenbecker, 2011). The ability of an athlete to generate large speeds increases the chances of them winning the point. Although these sports may be similar in nature there are many factors that can cause a difference in outcome.

Figure 1.1 - The badminton jump smash action (top) and the tennis serve action (bottom).

The rationale for this research study is to analyse the badminton jump smash and the tennis serve actions to gain an understanding of the effect of the interactions between aspects of the technique on speed and variability. This research will then focus on identifying similarities between the tennis serve and the badminton smash.

1.2 Statement of Purpose

The purpose of this study is to investigate technique in the badminton jump smash and tennis serve in terms of:

- contributions to pace
- outcome variability and technique variability

1.3 Research Questions

1. Which kinematic technique aspects of the badminton smash explains the most variance in smash speed?

In the badminton smash, the increasing speed of the shuttlecock can help determine the advantage of one player over another. Previous research into the badminton smash has focused on the wrist and forearm movements (Poole, 1970; Lui et al., 2002; and Waddell and Gowitzke 2000). However, none of these studies has taken into consideration how other body parts may affect the shuttlecock speed after impact. This analysis will allow those aspects to be identified and the mechanics of an optimal badminton smash to be understood.

2. What are the relationships between outcome and technique variability in the badminton jump smash?

By looking at speed variability any differences in technique between players who are more constant in their badminton jump smash speeds and less constant in their badminton jump smash speeds will be identified. In badminton previous studies have shown that for a successful smash to occur a player must have adequate rotation of the lower arm to be significant to elevated performance (Johnson and Hartung 1974). Tasai et al. (2000) concluded that the wrist joint exerted the greatest velocity and power in the badminton smash. The analysis performed will allow the interaction of the badminton smash technique and the after impact speeds to be investigated further.

3. Which kinematic technique aspects of the tennis serve explain the most variance in speed for the tennis serve in four directions?

In tennis serve speed is an important part of the serve performance. An increasing serve speed reduces the time for the opponent to prepare to return the ball successfully and increases the probability of the server's superiority in gaining a direct point (Vaverka and Cerosek, 2016). Although there has been multiple studies looking at the tennis serve (Bahamonde and Knudson, 2000; Elliott, 1988; Elliott et al., 1999) none of these looked at how serve technique may change when hitting towards the left centre, advantage, right centre, and deuce courts. This analysis will allow those aspects to be identified and better understand how direction of the tennis serve may affect technique and speed.

4. *What are the relationships between outcome and technique variability in the tennis serve?*

First by analysing the tennis serve data any differences in speed variability when hitting towards the four directions of the tennis court will be identified. Then by comparing the tennis players who were more constant in their tennis serve speed and less constant in their tennis serve speed when hitting down the left centre court line technique differences that may affect speed variability will be identified. The analysis performed will allow the interactions of the tennis serve speed variability and technique to be analysed.

5. *How does the badminton smash technique compare with the tennis serve technique?*

Badminton and tennis are two of the most popular racquet sports today. With the badminton smash and tennis serve consisting of similar overarm techniques it is natural to want to compare the two actions and see how they may differ.

1.4 Chapter Organisation

Chapter 2 – consists of a review of the current literature regarding performance for the tennis serve and the badminton jump smash. Research into links between aspects of the sporting action and speed mainly focused on the upper part of the body. Previous investigations into variability along with speed and accuracy trade-off are also reviewed.
Chapter 3 – describes the equipment and protocols used to collect the kinematic and anthropometric data. Details are provided regarding the participants, equipment used and the specific data collected. The methods used to fill gaps in the kinematic data and the filtering performed is also explained.
Chapter 4 – the number of segments used to represent the subjects are justified and the methodology used to define each segment explained. The calculations of technique parameters are defined and details of the statistical test performed on the data described.
Chapter 5 – 9 are written in the form of papers and address the five research questions posed. Chapter 5 uses stepwise linear regression to address relationships between badminton jump smash technique and shuttle speed. Chapter 6 considers the relationship between badminton technique and variability. Chapter 7 use stepwise linear regressions to address relationships between tennis serve technique and speed. Chapter 8 considers the relationship between tennis serve technique and variability. Chapter 9 compares the difference in findings between the badminton jump smash and tennis serve technique.
Chapter 10 – a summary of the thesis is given. This includes methods used, the results obtained, and possible limitations. The research questions are addressed and potential future studies are proposed.

CHAPTER 2: REVIEW OF THE LITERATURE

Movements of the shoulder, elbow, and wrist are thought to be an important part in developing speed in racket sports, and consequently have been the focus of a number of previous published studies. In this chapter, previous research into the badminton smash and tennis serve are reviewed. The chapter concludes by examining past research on speed verse accuracy, variability, and badminton and tennis comparison.

2.1 Introduction

Racket sports are characterised by a hand–held racquet that is used to propel a missile between two (or four) players with the purpose of placing the missile in such a position that one player is unable to return it successfully (Lees, 2002). Overarm movements are essential skills in different sport games (Wagner et al., 2012). This is true for sporting games that use a racket. Upper–body kinematics between the sports maybe similar, if they are similar then it may be possible to identify general motor patterns of overarm movements and adapt them to different sports (Wagner et al., 2012).

The success of many tennis players on the men's and women's circuits is at least in part due to their powerful serves (Elliott, 2001). The speed of a tennis serve is an important part of the server's performance. A higher speed reduces the time for the opponent to prepare to return the ball successfully and increases the probability of the server gaining a direct point (Vaverka and Cernosek, 2016). The tennis serve is the most complex stroke in competitive tennis (Kovas and Ellenbecker, 2008).

Critical biomechanical features are integral to an effective service action. For the tennis serve a number of body segments must be coordinated in such a way that high racket speed is generated at impact.

The badminton smash is a power stroke used to gain a point advantage the movements of the forearm and hand transmit the energy produced by the arm swing to the racket head, as well as increasing racket head velocity by rotating (Tang et al., 1995). When a player performs a smash, arm movement pattern plays an important role in the execution of the strokes (Ariff and Rambely, 2008). The pattern involved an overarm pattern, which is flexion of the elbow and medial rotation of the humerous during the forward of force producing phase.

Similar to tennis, a higher speed reduces the time an opponent has to return the shuttlecock and increases the probability of the server gaining a direct point. To execute the smash shot successfully certain biomechanical characteristics are required.

Due to the similarities between these two overhead power strokes the literature has been reviewed collectively.

2.2 Key Phases of Overhead Racket Strokes

2.2.1 Tennis

The tennis serve has been broken down into three phases: preparation phase, acceleration phase, and the follow-through phase (Kovas and Ellenbecker, 2011). These phases can be further broken down into their own stages: release, loading, cocking, acceleration, contact, deceleration, and finish (Figure 2.1). This is known as the 3-Phase, 8-Stage model of tennis serves.

THREE PHASES

Preparation Phase	From the first sign of movement until maximal external rotation of the shoulder. Which coincides at the point when the tip of the racket head points toward the ground
Acceleration Phase	Begins from maximal external rotation of the shoulder until the end of ball contact
Follow-Through Phase	Begins immediately post ball contact and continues through the end of the service motion

EIGHT STAGES

1. Start	
2. Release	From the start stage (ball and racket at rest) until the ball is released from the non-serving hand
3. Loading	From the release stage until a fully loaded lower body position. This position coincides with the elbows lowest vertical position and also maximum knee flexion
4. Cocking	From the end of the loading stage until maximal shoulder external rotation coinciding with the tip of the racket head pointing toward the ground
5. Acceleration	From end of the cocking stage until contact
6. Contact	The very short period where ball and racket impact
7. Deceleration	Following contact until the end of upper and lower body deceleration of the serve
8. Finish	The short period at the end of deceleration and before the initial movement to prepare for the next stroke

Figure 2.1 – Kovas (2011) 3 Phase, 8 - stage model of the tennis serve.

2.2.2 Badminton

The badminton smash has been divided into five phases: preparation phase, backswing phase, forward swing phase, and contact phases, and follow through phase (Harrison, 2011).

In the preparation phase the hitting arm is positioned so that the elbow is pointing outwards with racket perpendicular to floor. During the backswing phase the arm raises in arm raises in an upward motion prior to backswing. In the forward swing phase, the hitting arm is at maximal extension prior to the height of contact. In the point of contact the wrist is flexed and snaps in a forward extension for greater impact. Lastly, in the follow through phase of the badminton smash the arm swings through in a forward diagonal motion, before returning to the ready position (Hewlett and Holland, 2016), (Figure 2.2).

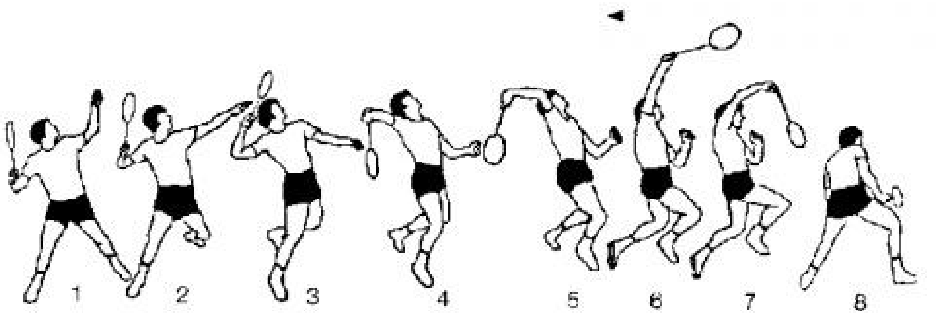


Figure 2.2 – Badminton jump smash technique.
(https://jordynhealy.wordpress.com/biomechanical - analysis/).

2.2 Biomechanics of Overhead Racket Shots

2.2.1 Evidence of a Kinetic Chain

Tennis and badminton requires sequenced activation of muscles and movement of bones and joints to achieve the motions, positions, and velocities seen in a player. This sequencing is known as the kinetic chain. A kinetic chain is the idea that the movement of neighbouring segments affects one another within a kinetic link (Figure2.3).

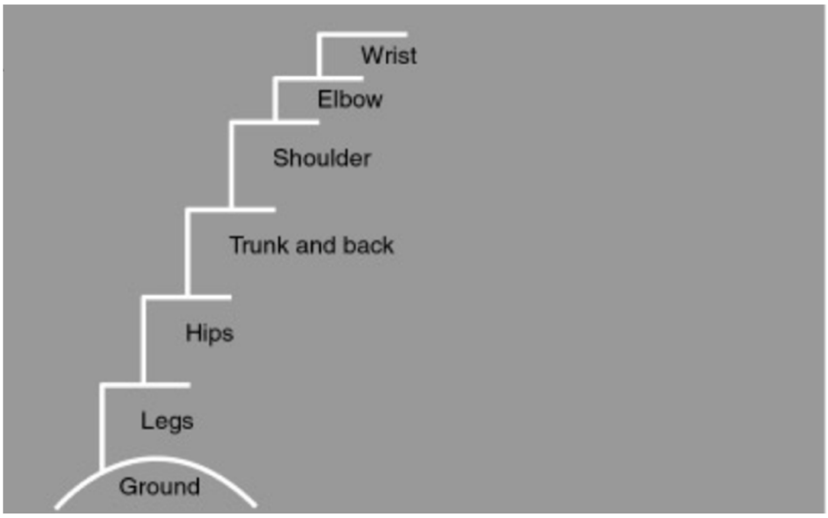


Figure 2.3 – Illustration of the kinetic chain in racket sports.
(http://biomechanicalprinciplesoftennisserve.blogspot.co.uk/).

The kinetic link principle states in order to produce the largest possible speed at the end of a linked chain of segments, the motion should start with the more proximal segments and proceed to the more distal segments, where the more distal segment begins its motion at the time of maximum speed of the proximal one, with each succeeding segment generating a larger end-point speed than the proximal segment (Marshall and Elliott, 2000). '*In the tennis serve two movement strategies are critical in this respect: (i) proximal-to-distal firing patterns, and (ii) active acceleration–deceleration of body segments.*

Research evidence suggests that a proximal-to-distal firing pattern is the most effective for increasing the racket-head speed in the serve. In such a sequencing pattern, the stronger more heavily muscled proximal joints should become activated before the weaker but faster distal joints. This firing pattern has proven the most efficient due to the fact that it takes advantage of each joint's linear and angular momentum generating characteristics.

A second characteristic of efficient movement coordination in the serve is consecutive acceleration and deceleration of the main body segments. When done well this permits the player to achieve racket-head speeds far greater than they would if they did not use an optimal acceleration- deceleration coordination pattern. The mechanism for this benefit is the transfer of both linear and angular momentum. This movement strategy aids in the transfer of momentum from the lower extremity to the upper, and from the upper extremity to the racket-head.

These two kinetic-chain patterns combined; generate a whip–like motion: when the upper leg and trunk musculature are the first to contract, greater separation is developed between the shoulders and hips which results in a whip effect as the hips are decelerated and the shoulders accelerate as they uncoil and the shot is released (Ivaneciv, et al., 2011).'

This was backed up by a 2008 study by Hirashima et al. who looked at the effects of the kinetic chain in the baseball pitch. They found that shoulder horizontal flexion prevented the upper arm from lagging behind relative to the trunk. Thus, the angular velocity of the upper arm increased with that of the trunk. The study also found that velocity-dependent torques at the shoulder, elbow, and wrist were produced as a result of the velocity that was produced by the trunk and shoulder joint torques in earlier phases.

The kinetic chain has also been investigated in overhead racket sports (Elliott et al., 1986;

Van Gheluwe and Hebbelinck, 1983) and proximal to distal sequencing has been observed (Figure 2.3).

Table 2.1 – Coordination of kinetic chain on body segments in racket sports (Elliot, 1988).

Power Stroke (the service)
Leg drive and trunk rotations → shoulder speed (forward/shoulder-over-shoulder/twist)
+   Upper arm elevation and flexion → elbow speed
+   Forearm extension and pronation and upper arm internal rotation → wrist speed and racket orientation
+   Hand flexion → racket speed

Elliot et al. (1999) indicated how endpoint velocity in tennis was achieved using the movement of lower limbs and the upper limbs (Table 2.1). Each of these segments in the kinetic chain has been investigated individually with respect to end point velocity (ball speed).

2.3.2 Lower Limbs

The leg drive is the first step in the kinetic chain for both the tennis serve and badminton smash. In the tennis serve, dynamic lower-limb motion is considered the origin of the tennis serves' kinetic chain (Reid et al., 2008). The lower limb drive not only begins the drive to the ball but it also assists in increasing the range of racket movement (Elliot, 1988). It has also been considered a precursor to high-speed trunk and upper extremity segment rotations (Reid et al., 2008). Lower limbs generate about 50% of the total force developed during the tennis serve. A 2012 study down by Sweeny et al. found that there was a strong relationship between the upward drive of the hitting shoulder and the serve speed, this was helped impart by the drive from the lower limbs. Elliott et al. (1998) indicated how end point velocity in tennis was achieved using the movement of the lower limbs, the trunk and the upper limbs (Table 2.1). Each of these segments on the kinetic chain has been investigated individually with respect to end point velocity (ball speed).

In 2007 Girard et al. examined the influence of restricting knee motion during the serve in tennis players of different levels. They found that across each group when lower limb movement was restricted, lower ground reaction forces were found (Figure 2.4). It was suggested that the lower extremities require some degree of knee flexion during the backswing to generate large amounts of linear and angular momentum during knee extension, transferring the GRF to the trunk.

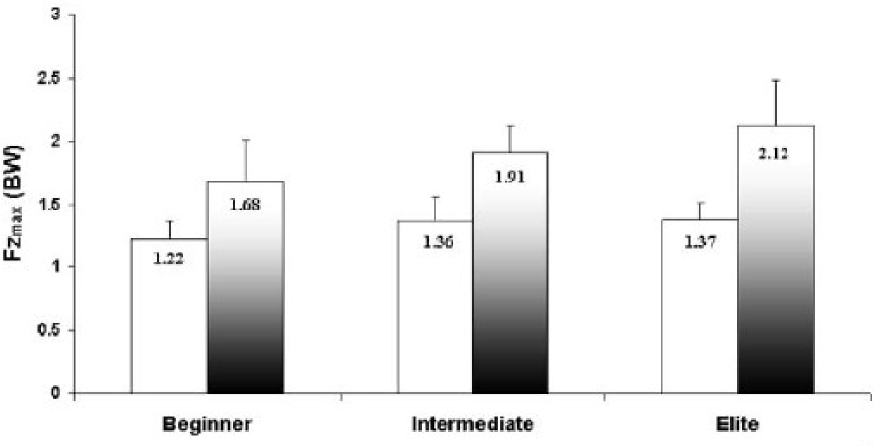


Figure 2.4 – Vertical maximum component of ground reaction forced during flat serve (restricted serve white bar) and normal (normal serve grey bar) knee motion 3 performance level groups (Girard et al., 2007).

Fleisig and et al. (2003) reviewed the tennis serves of 22 Olympic male tennis players using high speed cameras at the Sydney games and found that as tennis players release the ball in their service motion they tend to flex both knees. They also found that the players then extended both knees to move their body upward and this movement influenced the upper limbs in combination with the torso segment with maximum angular velocity of knee extension occurring 180 ms before ball impact.

To date this date research into the lower limb drive and the badminton jump has not been found.

2.3.3 Trunk

The trunk is considered a major link in the kinetic chain of overhead racket shots since it transfers the momentum built in the lower limbs to the upper limbs. Rotation of the trunk during the tennis serve is an integral part of the development of power and transfer of energy up the kinetic chain from the lower to the upper extremities (Ellenbecker and Roetert, 2004). Previous research has shown that trunk rotation is a major contributing factor to the final racket speed. A result repeated by Elliott et al. (2003) who stated that trunk rotation is important in powerful hitting movement where the hip and shoulder rotations are the most significant source of power for ground strokes. Bahamonde (1999) reported a relationship between trunk rotation and racket velocity he concluded that one of the most important elements of the forehand and backhand strokes was the development of optimal trunk rotation since trunk rotation was highly correlated with racket velocity.

Furthermore, Martin et al. (2013) examined the relationship between segmental angular momentum and ball velocity in ten professional tennis players and found that there were correlations between mean angular momentum of the trunk and ball velocity about the transverse and anteroposterior axes. Trunk rotation has been shown to influence the forward movement of the shoulder in a positive way, thereby increasing the speed of the racket. Fleisig et al. (2003) found that maximum trunk tilt angular velocity occurred at 0.076s before impact and that maximum upper torso angular velocity preceded maximum pelvis velocity and the trunk contributed to ball velocity since its acceleration was associated with an explosive contraction of the internal rotators of an abducted shoulder.

To date this date research into the movement of the trunk and the badminton jump has not been found.

2.3.4 Upper Limb

The upper arm segment allows the momentum built up by the lower limbs and torso to transfer towards the end point at the distal end of the upper limbs. The shoulder joint allows this transfer to occur and has been shown to be associated with the end point velocity in overhead racket shots.

In tennis, the shoulder joint is integrally involved in the service action and is believed to contribute ~20% of the total force generated during the stroke (Reid et al., 2007). Internal shoulder rotation has been shown to contribute to produce a high velocity tennis serve (Elliott, 1995). Gordon and Dapena (2006) meanwhile found that the speed of the racket head at impact was associated with external rotation of the shoulder during the backswing phase. Indicating the range of motion may also be crucial to racket head velocity.

Sprigings et al. (1994) and Elliott et al. (2003) reported that high angular velocities of shoulder internal rotation were observed just before impact, and concluded that this movement contributed to the development of racket head velocity at impact. This was also observed in a study by Tanabe and Ito (2007). When analysing the tennis serves of 66 male tennis players the angular velocity of internal shoulder rotation increased just before impact with a mean contribution of 41.1% of horizontal racket head velocity at ball impact were high. The timing of the internal shoulder rotation occurs as soon as the angular velocity of the shoulders adduction begins to decrease (Fortenbaugh et al., 2009).

Elliot et al. (1995) reported that shoulder internal rotation generated approximately 50% of the linear racket head velocity. The strength of the shoulder has also been investigated with respect to racket head velocity. Cohen et al. (1994) found that internal shoulder rotation and shoulder flexion at 0° abduction were correlated to serve velocity.

In badminton, Adrian and Enberg (1971) emphasized the importance of lateral rotation at the shoulder joint prior to the forward motion of the shoulder and elbow to increase racket head velocity.

2.3.5 Forearm

The forearm is the penultimate segment in the kinetic chain and transfers the momentum from the upper arm to the hand/racket segment. The elbow, the link between the upper arm and forearm predominately uses two movements in the service action: pronation and extension. Previous research has shown that flexion and extension of the elbow is important in generating racket head velocity (Kibler, 2007; Cohen, 1994; Elliott, 2006; Tanabe, 2007). The fastest servers' exhibit more flexed elbow joint reducing the inertia of the arm during shoulder internal rotation creating a larger effect on racket speed. High - speed video analysis by Kibler (2007) has demonstrated that during the service the elbow moves from 116° to 20° with ball impact occurring at approximately 35°. Cohen (1994) found that the rate of torque development for elbow extension was also correlated with serve velocity.

Previous work has also identified the role of elbow (radio–ulnar) pronation in orientating the racket appropriately for impact (Elliott, 2006; Elliott et al., 2003). Although pronation of the forearm does not generate a great deal of racket head speed it is essential in the orientation of the racket face to the ball. In 2007, Tanabe found that the forearm works to develop horizontal racket head velocity for slow servers and to adjust the racket face in the proper direction for fast servers.

In badminton, Tang et al. (1995) analysed the movements of the forearm during the smash movement using three-dimensional cinematography. It was found that greater velocities of the racket head were produced from pronation of the radio- ulnar joint and ulnar flexion. This was also found by Salim et al. (2010) who examined the arm movement of 14 male and female players. They suggested that forearm rotation and elbow extension were correlated with smash speed whilst also observing that the peak rotation angular velocity of the forearm occurred at shuttle contact and that the elbow was extending throughout contact. Johnson and Hartung (1974) concluded that rotational movements of the lower arm (pronation and supination) were significant to elevated performance.

2.3.6 Hand/Racket

The last segment in the kinetic chain of an overhead shot is the flexion of the hand and racket about the wrist joint (Elliott, 1988). In tennis, Elliott et al. (2003) concluded that wrist flexion increased racket speed and it commenced prior to ball impact in all the players observed.

In badminton, Tang et al. (1995) suggested that palmar flexion of the wrist was a factor in attaining greater racket head velocities with the movement occurring throughout contact. Tsai et al. (2000) agreed, discovering that the wrist joint was the joint with the greatest velocity and power in all three badminton strokes (clear, drop and smash), although this would be expected within a proximal to distal kinetic chain. However, Waddell and Gowitzke (2000) argued that the power emanated from the forearm segment and that palmer flexion was clearly not involved in generating racket head speed. Poole (1969) and Rantzmayer (1997) support this theory by suggesting that we rarely 'snap' the wrist and that power strokes such as the smash are made with forearm pronation. Gordon and Dapena (2006) found that the wrist position as the racket approaches its lowest position may also be an indication to predict racket head speed in tennis. They found that the larger the wrist extension in this position the greater the racket head speed.

2.3.7 Studies on joint contributions

Few studies have attempted to quantify the amount each joint contributes to racket head velocity across the kinetic chain. Gowitzke and Waddell (1977) estimated that joint contributions made to the velocity of the shuttle in the badminton smash attributed 53% of the final output to upper arm rotations and forearm pronation. Lui et al. (2002) also suggested the movements of the arm during the badminton smash were important. They found that the movements of the arm are the greatest contributors to racket head speed with upper arm internal rotation, lower arm pronation and wrist palmar flexion contributing 66%, 17% and 11% respectively. Also, Rambely et al. (2005) again indicated that the movements of the arm were the most important in generating racket head speed when analysing 13 male players performing the smash in badminton. They found that the wrist contributed the most to the racket-head velocity (26.5%), whilst the elbow and shoulder joint contributed 9.4% and 7.4%, respectively.

2.4 Speed-Accuracy Trade-Off

The speed accuracy trade-off phenomenon is one of the most often observed occurrences in movement behaviour (Ciapponi, 2016). It states that an individual who is performing a skill will sacrifice speed for accuracy or vice versa. In both the badminton jump smash and tennis serve it is important for the players to produced high velocities post-impact while being accurate. Hitting the ball or shuttle with a high velocity while not being accurate may cause the player to lose a point. However, hitting the ball or shuttle with less speed in order to be more accurate may give the opposing player more time to react and dominate the point. Therefore, it is important in both sports for players to reach the correct balance in order to produce a successful serve or smash.

Evidence of the speed-accuracy trade-off have mostly been found in sports where the reduction in speed doesn't have a detrimental effect to the outcome of the success of the skill. For example, in darts where the velocity of the throw doesn't determine the outcome, Etnyre (1998) have found that accuracy decreases when speed is emphasized. This has also been shown in cricket fielders when the accuracy of the throw is normally more important than its velocity. Freeston et al. (2007) found during a study of 110 cricket players that optimum throw velocity was between 75- 85% of maximum throwing velocity for accuracy.

In sports where the speed impacts on the successfulness of the outcome of the skill, the speed-accuracy trade-off is used less. For example, in tennis, Cauraugh (1990) investigated the correlation between ball velocity, accuracy and variability in 15 players and found that no correlation between ball velocity and accuracy existed. Although the study didn't investigate targeting and it is common knowledge that tennis players reduce the velocity of their second service in order to ensure accuracy and reduce the likelihood of second service fault and the loss of the point. Van Den Tillar and Ettema (2006) also found that baseball pitchers reduced velocity when asked to target but this did not improve their accuracy however suggesting it may not have been a practiced skill. This may be confirmed by the finding by Garcia et al. (2013) who suggest that more skilled performers are able to maintain their accuracy at greater velocities. They found that novice players reduced their speed for accuracy compared to an expert group who managed to maintain their speed without being less accurate.

2.5 Variability

Variability appears as a distinguishing feature of someone's behaviour and even of their ability to perform a movement in a particular environment (Antunez et al., 2012). Far from being understood as harmful for performance, new research suggests that when variability appears in motor performance, it may be beneficial for movement organisation and performance (Antunez et al., 2012). In multi-joint tasks that require precision of an endpoint effector, the variability of individual segments trajectories may be greater than the variability of the end point. This was shown best by Bernstein (1967) where the movement of professional blacksmiths was described when repeatedly hitting a chisel. Considerable variability was observed for individual joints of the upper body, yet the trajectory of the hammer tip was consistent with each strike, particularly at the point of impact (Horan et al., 2011).

Hernandez–Davo et al. (2014) examined the effects of variable training on velocity and accuracy in the tennis serve. By looking at 30 tennis players they were able to find that the players who had variable training were able to improve both velocity and accuracy compared to those without.

In 2012 Antunez and colleagues examined 17 tennis players and found that when the variability of the speed of the hand holding the racket was increased, accuracy was decreased. The results also show that an increase in the amount of variability in some kinematic variables is related to a decrease in serve speed.

2.6 Badminton Jump Smash verses Tennis Serve

The tennis serve like the badminton smash uses an overhead technique in order to complete the sporting action. It is because of this similarity that it is reasonable to look closer at the two sporting actions and compare the differences.

One obvious difference between the two sports is the rackets and projectile object. In badminton players use a more lightweight and smaller racket compared to tennis. The projectile in badminton is a shuttlecock made up of 16 feathers with a diameter around 65 mm and weighs around between 4.75 g - 5.50 g. This is lighter and has more drag than a tennis ball which sphere weighing between 56 g - 59.4 g with a diameter between 65 mm - 3 mm. The weight for the racket is also different to each other. The badminton racket weighs between 60 g - 100 g while the tennis racket weighs between 245 g - 340 g (Figure 2.5).

Figure 2.5 – Comparison of badminton racket and shuttlecock against the tennis racket and ball.

Racket string tension is also thought to play a role in speeds after impact for racket sports. A 1978 study done by Baker and Wilson found that average and flexible rackets have the highest ball speed after impact when strung at 50-pound tensions. A stiff racket was not influence significantly by different string tensions. In 2006 a study by Cross and Bower examined the effects of swing-weight on swing speed and racket power. They found that swing speed decreased as swing-weight increased. The results showed that although the changes in power were small, these small changes can make a significant difference to the result of a particular shot.

While the movements of the badminton smash and tennis serve may be similar the control over the impact location is different. In tennis the player who is serving has control of the location of the ball at impact due to the ball toss. This is not the case in badminton where the smash is used in response to an opposing player's previous shot.

Similarities exist in the joint movements used to generate racket head velocity (Table 2.2). Previous research has shown that both movements use shoulder internal rotation to generate high velocity tennis serves (Reid et al., 2007; Elliot et al., 1995; Gordon and Dapena, 2006; Sprigings et al., 1994; Elliott et al., 2003) and high velocity badminton smashes (Lui et al., 2002; Adrian and Enberg, 1971). Forearm pronation has also been linked to increasing the velocity of both skills (Tang et al., 1995; Elliott 2006; Elliott, 2003). The role of wrist plantar flexion has been mixed on racket head velocity (Elliott, 1998; Elliott et al., 2003; Tang et al., 1995; Waddell and Gowitze, 2000; Poole, 1969; Rantzmater, 1997). The earlier segments of the kinetic chain of the overhead racket shot have received some focus in tennis (Elliot et al., 2003 Elliott et al., 1986; Van Gheluwe and Hebbelinck, 1983) but not been researched in badminton.

	Subjects	**Sport**	**Shoulder Internal Rotation**	**Shoulder Abduction**	**Elbow Pronation**	**Wrist Flexion**
Springing et al. (1994)	1 player	Tennis	29.7	24.1	14.8	26.0
Elliot et al. (1995)	11 male players	Tennis	54.2 ± 14.1	12.9 ± 5.9	5.2 ± 4.1	30.6 ± 9.1
Lui et al. (2002)	6 female Singapore National players	Badminton	66.0		17.0	11.0
Elliott (2006)	Review	Tennis	40		5	30
Gordon & Dapena (2006)	9 intercollegiate players	Tennis				30.0
Tanabe & Ito (2007)	66 male players	Tennis	41.1 ± 14.7		3.6 ± 5.0	31.7 ± 7.5

Table 2.2 – Comparison of joint contributions to post impact speeds in the badminton smash and tennis serve.

2.7 Chapter Summary

Previous research has shown leg drive to be important to kinetic chain in racket sports by providing the momentum needed to complete the sporting actions. The energy that is needed to produce high speeds is transferred to the racket via the lower limbs. The shoulder joint allows for transfer of momentum and contributes to the end point velocity in both the badminton smash and the tennis serve. The forearm and wrist has been shown to be important in the placement of the racket face during the badminton smash. String tension and racket weight has also been found to play an important role in the speeds after impact in racket sports.

CHAPTER 3: DATA COLLECTION AND PROCESSING

This chapter describes the equipment and protocols used to collect the kinematic from the subjects. Details are provided regarding the participants, equipment, setup and calibration, marker positions, trials captured and the anthropometric measurements recorded. The methodology used to process kinematic data, namely the filling of gaps in the time-history of marker positions and the filtering applied are also described.

3.1 Equipment

3.1.1 Badminton

Data were collected over two separate data collection sessions (December 2013, March 2014) at Loughborough University Royce Dining Hall and Sir David Wallace Sports Hall. The equipment, layout, and procedures used were the same in all data collection sessions.

Figure 3.1 – The data collection environment Royce Dining Hall (top) Sir David Wallace Sports Hall (bottom).

A Vicon Motion Analysis System (OMG Plc, Oxford UK) was used to collect kinematic data. Eighteen cameras, operating at a frequency of 400 Hz were positioned to cover a volume of approximately 7 x 3 x 3 m (Figure 3.1). The Vicon Motion Analysis System's accuracy is also reduced when cameras can see each other in their field of view. To avoid this, the Vicon cameras were mounted on tripods with 1 m extension poles attached, allowing the cameras to be pointed downwards slightly. The use of a frequency of 400 Hz was decided by choosing the best frequency that allowed for picking up the most markers throughout the sporting action while capturing at a high frequency.

The Vicon system was calibrated at the start of each day of data collection using an Ergocal (14 mm markers) static calibration frame, to define the origin and global coordinate system, and a 240 mm calibration wand (14 mm markers). When viewed from behind, the x-axis point from left to right, the y-axis pointed forwards and the z-axis was the upwards vertical.

The use of Two Phantom v4.1 digital high - speed cameras were used to capture all badminton jump smash trials. Even though this footage was not used directly in this thesis, it provided a useful source of reference for analysing the badminton jump smash technique. Both cameras recorded at a frequency of 500 Hz and were positioned in front of the participant and to the side (3.2).

Figure 3.2 – Images obtained from the two high – speed video cameras during data collection sessions.

3.1.2 Tennis

Data were collected over two separate data collection sessions (December, 2015) at Loughborough University and Gosling Tennis Centre, Welwyn Garden City. The equipment, layout, and procedures used were the same in all data collection sessions.

Figure 3.3 – The data collection environment Loughborough University Tennis Centre (left) Gosling Tennis Centre (right).

A Vicon Motion Analysis System (OMG Plc, Oxford UK) was used to collect synchronous kinematic data. Eighteen cameras, operating at a frequency of 400 Hz were positioned to cover a column of approximately 7 x 3 x 3 m (Figure). The Vicon Motion Analysis System’s accuracy is also reduced when cameras can see each other in their field of view. To avoid this, the Vicon cameras were mounted on tripods with 1 m extension poles attached, allowing the cameras to be pointed downwards slightly.

The Vicon system was calibrated at the start of each day of data collection using an Ergocal (14 mm markers) static calibration frame, to define the origin and global coordinate system, and a 240 mm calibration wand (14 mm markers). When viewed from behind, the x-axis point from left to right, the y-axis pointed forwards and the z-axis was the upwards vertical.

3.2 Participants

3.2.1 Study 1

Twenty-five county level badminton players were tested over the course of one data collection session. All badminton players were identified as county level up to members of the England squad. Seven players were eliminated from the study as they did not perform a sufficient number of proper jump smashes to be included in the study. The remaining eighteen players form the basis of this investigation (mean ± standard deviation: age 24.9 ± 6.5 years; height 1.84 ± 0.08 m; body mass 78.9 ± 9.0 kg). See Appendix 1 for details of each individual's data.

3.2.2 Study 2

Thirteen badminton players were tested over the course of one data collection session. All badminton players were identified as playing on the Loughborough University badminton team up to the current England squad. Four players were eliminated from the study as they did not perform a jump smash for inclusion of the research. The remaining nine players made up the basis of this investigation (mean ± standard deviation: 22.8 ± 6.0 years, 1.76 ± 9.2 m, 75.0 ± 10.4 kg). See Appendix 1 for details of each individual's data.

3.2.3 Study 3 and Study 4

Nineteen tennis players were tested over the course of two data collection sessions. Two players were eliminated from the study as the motion capture system did not accurately track a sufficient number of tennis serves with crucial markers remaining affixed to their body. The remaining seventeen tennis players formed the basis of the tennis investigation (mean ± standard deviation: 19.8 ± 2 years, 1.83 ± 5 m, 75 ± 7 kg). See Appendix 1 for details of each individual's data.

All subjects were deemed fit to participate and had no injuries within six months of the data collection sessions. The testing procedures were explained to each subject in accordance with Loughborough University ethical guidelines an informed consent form was signed (Appendix 2). All subjects conducted a thorough warm-up prior to commencing data collection.

3.3 Markers

Forty-seven 14 mm retro-reflective markers were attached to each subject using a sports adhesive spray and double-side tape. Markers were placed over the bony landmarks of each participant (Figure 3.4). Detailed of the marker positions are provided in Appendix 3.

Figure 3.4 – An illustration of the position of the forty-seven body markers used for both studies.

Eight patches of reflective tape were attached to the badminton racket (Figure 3.5). An additional marker, in the form of a patch of reflective tape was attached to the shuttlecock. Six patches of reflective tape were attached to the tennis ball (Figure 3.5) and eight patches of reflective tape on the racket (Figure 3.5), enabling ball speed, racket angle, and the instant of contact to be determined.

Figure 3.5 – Illustration of the markers on the shuttlecock, ball, and rackets used in the studies.

3.4 Testing Protocol

Data collection commenced with the acquisition of a static trial; with the subject standing in an anatomical position with their arms straight out holding a racket (Figure 3.6). This trial enabled the length of the body segments to be determined and joint offsets angles to be calculated (see Chapter 4).

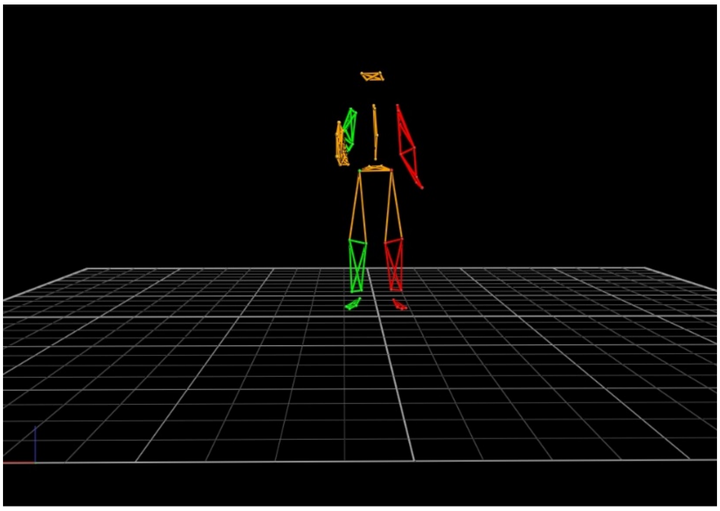


Figure 3.6 – Static trial of participant used in both studies.

A range of motion trial was performed, following the outline of Ranson et al. (2008) to determine the range of motion of a lower back reference frame relative to the pelvis reference frame. Participants were given a demonstration on how to move to their end of range of active lower trunk rotation, side flexion to both sides, and left and right axial rotation. Participants were instructed to keep their legs straight throughout the trial and to maintain a static pelvis position while side - flexing and rotating their trunk. Hence, the proportion of available lower back range of motion using during the sporting actions could be determined. A neutral position of the spine was obtained from the range of motion trial. This was defined to be the moment the spine passed though the vertical as the players went from side-flexion one way to side-flexion the other way. From this orientation angles of the lower back relative to the pelvis to be normalised (see Chapter 4). Subjects then performed maximum velocity trials of either the badminton jump smash or tennis serve.

3.5 Anthropometric Data

Segmental inertia parameters for each subject were required as an input to the models developed; these were determined using Yeadon's geometric model (1990). This model has been used successfully in previous studies, enabling subject - specific inertia parameters to be determined for subjects with little inconvenience caused to them. Ninety-five anthropometric measurements were taken at specific points on the body by an experienced researcher, these included: lengths; widths; depths; and perimeters. This enabled the body to be split into the required segments. Yeadon's model used the segmental density values of Chandler et al. (1975) as initial estimates and subsequently varied these values within a subroutine until there was a match between the whole body mass determined by the model and the subject's body mass as measured using Seca Alpha digital scales.

3.6 Data Processing

Prior to analysing the techniques used by the participants, kinematic data were filled (where necessary) and filtered; and the key instants in the action were also identified. Although effort was made to maximize the accuracy of the data, due to the dynamic nature of the badminton jump smash and the tennis service actions, some small gaps were present in the marker trajectories during the actions. Also, there was some noise within the data; this is thought to be because of the markers wobbling on the skin or due to not being able to track all the markers throughout the entire action.

3.6.1 Identification of Crucial Instants

In order to compare and process trials appropriately, it was necessary to identify the frames corresponding to: preparation phase (PREP), the end of the retraction phase (ER), the racket lowest point phase (RLP), and shuttlecock contact (SC). The PREP frame was defined as the point at which the participant's knees were more flexed prior to jumping. The ER was identified by the maximum horizontal position of the racket behind the participant prior to the backswing. The instant of racket lowest point (RLP) was identified as the minimal vertical position of the racket prior to the forward swing of the racket. The SC frame was identified as the first frame that the racket head made contact with the shuttle or ball. In order to calculate minimal external shoulder rotation the instant was not defined through observation of each frame, due to difficulty in identifying the specific point. Therefore, the time histories of each joint movement were used and the external rotation value was used (Figure 3.7).

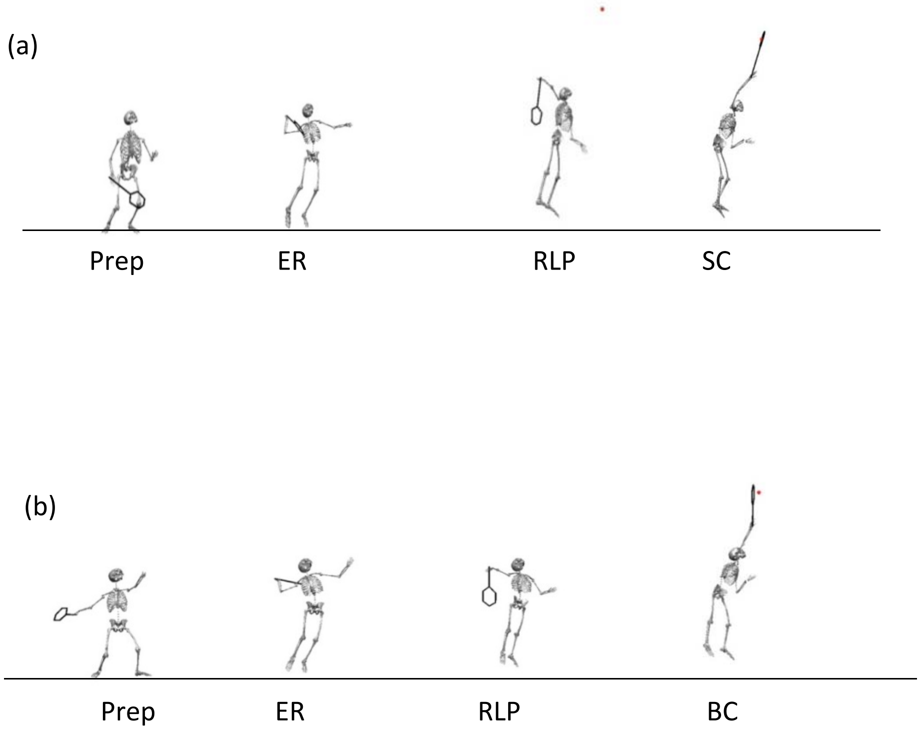


Figure 3.7 – Key instants of the (a) badminton jump smash and tennis serve (b) used in the studies.

3.6.2 Gap Filling

Very few gaps were present in the Vicon data during the specific period of interest in the badminton smash action. The gaps were filled using the 'spline filled' and 'pattern filled' functions within Vicon's BodyBuilder software; a spline is fitted to the data either side of the gap or interpolated to estimate the missing values. On each occasion filling was performed, the new data was visually inspected to ensure the filled values were sensible.

3.6.3 Filtering

All marker trajectories were filtered prior to being used in the model. Although these trajectories were relatively smooth, noise was magnified when differentiated in order to calculate velocities and accelerations. All kinematic data were filtered using a fourth order Butterworth filter (double–pass) with a low pass cut-off frequency. Cut-off frequencies were evaluated using a residual analysis. The decision of the frequency to use was a compromise between the amount of signal distortion and the amount of noise allowed through; the method suggested by Winter (1990) was used, assuming both errors to be equal. A residual analysis examines the difference between the raw and filtered kinematic pattern over different frequencies. The choice of optimal frequency was a compromise between the extent of signal attenuation and the amount of noise allowed to pass through. A cut-off frequency of 30 Hz were chosen to be applied to all marker positions except for the shuttlecock and ball in order to not distort impact velocities.

3.7 Chapter Summary

The chapter has provided details of the testing procedures used in the four data collection sessions and details of the chapter participants involved in this study. Marker positions were described and the data processing required prior to trials being analysed. The methods used to fill gaps in the marker trajectories have been illustrated and the level of filtering applied justified.

CHAPTER 4: DATA ANALYSIS

This chapter provides details of the segmentation of the body and the location of joint centres for an eighteen segment representation of the human body. The calculations of the parameters used in subsequent chapters are explained. In addition to the statistical tests performed.

4.1 18 Segment Representation of a Participant

A whole-body analysis was performed using BodyLanguage, within Vicon's Bodybuilder software (Appendix 4). The body was represented by a system of 18 rigid segments: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two segment foot. A local coordinate system was defined for each segment using three markers on the segment itself. This allowed segment orientations and joint angles to be calculated (Figure 4.1).

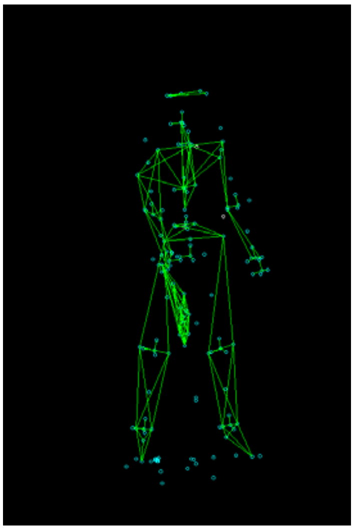
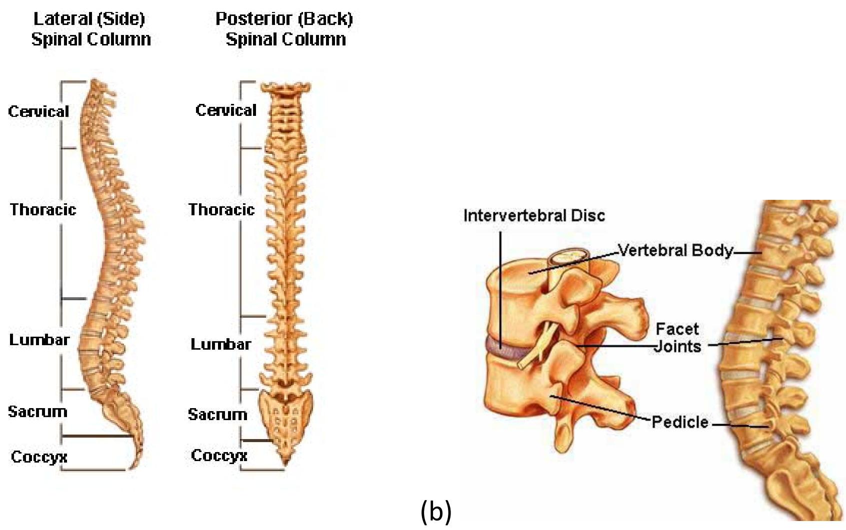


Figure 4.1 – Illustration of the 18 - segment representation of the human body.

4.2 Segmentation of the Back

During both the badminton jump smash and the tennis service actions, the spine goes through a number of complex motions. Although parts of the spine have 6 degrees-of-freedom: the discs are able to deform, allowing the vertebrae to rotate and translate; the spine as a whole is only able to produce flexion - extension, lateral flexion and axial rotation (Zatsiorsky, 1998). The spine's flexibility varies along its length (Figure 4.2). The thoracic spine can only produce limited amounts of flexion - extension and lateral bending, due to its thin intervertebral disks, the configuration of the articular facets, and the apposition of the spinous processes. Also, the connection of the facet joints to the ribs and the sternum also reduces the mobility of the thoracic spine. The thicker intervertebral discs in the lumbar region of the spine allow large amounts of flexibility in flexion - extension and lateral bending, but axial rotation is restricted due to the articular facets. The cervical region exhibits three degrees-of-freedom due to the occipital - atlanto - axial complex which has as two rotational degrees-of-freedom and the atlas which can move independently (Zatsiorsky, 1998).



(a) (b)

Figure 4.2 – (a) Illustration of the sections of the spine (b) and spinal facet.
https://www.spineuniverse.com/conditions/spinalfractures/anatomy-spinal-fractures

In the current study, in order to calculate meaningful parameters describing the motion acting in the lower back of both tennis players and badminton players, it is critical that the back is represented in enough detail. Roosen (2007) conducted range of motion trials comprising flexion - extension, lateral bending and axial rotation of the spine. No movement was found to occur between the head and the cervical spine; therefore, he concluded that the head and cervical spine could be modelled as a single segment. It was therefore decided that three back segments would be used in the current study: lower back, upper back, head and neck. These segments will be defined later in this chapter.

4.3 Joint Centre Locations

A pair of markers was positioned across each joint, such that their mid-point coincided with the joint centre. The only exceptions were the hip, back and head and racket segments. The pair of markers were positioned so that their mid - point coincided with the joint centre when the segment was in a typical orientation of the movement e.g. the shoulder markers were positioned with the shoulder in a relatively flexed position, i.e. pointing upwards (overhead). The method for calculating the joint centres of the back are described below.

4.3.1 Hip Joint Centres

The hip joint centres (RHJC and LHJC) were calculated using the algorithm of Davis et al. (1991), based on the radiographic examination of 25 hip studies. The coordinates of RHJC and LHJC, relative to a local pelvis coordinate system (defined in Section 4.4.1), were:

$$Xcoordinate = S[\ Csin(28.4) - \frac{d_{ASIS}}{2}]$$

$$Ycoordinate = [-x_{dis} - r_{marker}\ ]\cos(18) + Ccos(28.4)\sin(18)$$

$$Zcoordinate = [-x_{dis} - r_{marker}]\sin(18) - Ccos(28.4)\cos(18)$$

Where,

S = + 1 for the left side; and -1 for the right side

A leg length was calculated for each leg, during a static trial, as the distance from the hip joint centre to the lateral ankle marker, going via the lateral knee marker. The mean of

these two values was defined as LegLength.
C (m) = 0.115*LegLength – 0.0153

dASIS (m) = distance between the bony protrusions on the left and right anterior superior iliac (LASI and RASI, respectively).

r (m) = marker radius.

xdis (m) = anterior / posterior component of the ASIS / hip centre distance in the sagittal plane of the pelvis and measured during clinical examination. This was estimated, as in Vicon's generic *Golem* model, using the formula:

xdis = 0.0001288 * LegLength – 0.04856.

4.3.2 Joint Centres of the Back

Joint centres for the lower back (LOWJC), upper back (MIDJC) and the head and neck segment (TOPJC) were defined using the methodology of Roosen (2007). The LOWJC, MIDJC and TOPJC were calculated using the positions of the anatomical markers located on the left and right superior iliac (LASI and RASI), the left and right posterior superior iliac (LPSI and RPSI), the proximal (sterna) and distal (clavicular) end of the sternum (STRN and CLAV) and the spinous processes of T10 and C7) (Worthington, 2013). The exact location of the markers can be found in Appendix 3.

4.3.3 Racket Centre

A racket centre was calculated for each trial using the four side markers on the head of the racket (Figure 4.3).

RACKETCENTRE = (R4 + R5 + R7 + R8) / 4

Figure 4.3 – Illustration of the orientation of the racket head markers.

4.4 Segment Definitions

In the BodyLanguage code each segment was represented by a right - handed coordinate system. These were positioned at the lower joint centre of the segment when standing in an anatomical position. Segments were defined such that when in an anatomical position, the z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed to the subject's right (representing the flexion - extension axis of the joint) and the y-axis pointed forwards, representing the frontal axis (Figure 4.4). The longitudinal axis was typically defined to join the proximal and distal joint centres of the segment, exceptions to this are described below.

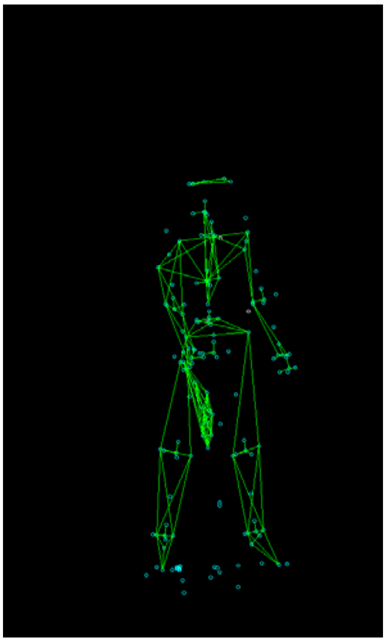


Figure 4.4 – Illustration of the orientation of the 18 segments' coordinate axes of the body.

A local coordinate system was defined for each segment by specifying the origin, two defining lines and the order of axis specification:

e.g. *Segment = [Origin, 1st Defining Line, 2nd Defining Line, Axis Order (e.g. zyx)]*

In this case (with axes being specified in the order xyz),

z-axis = 1st Defining Line

y-axis = (2nd Defining Line) × (1st Defining Line)

x-axis = the coordinate axis required to complete a right-handed coordinate system.

In general, segments were defined using a zyx axis order, specifying the z-axis (longitudinal axis of the segment) directly. A vector joining the pair of markers at the joint (parallel to the sagittal axis of the segment) was used as the second defining line. This corresponds to the recommended format of segment definitions in

BodyBuilder (Oxford Metrics Ltd., 2002). The exceptions when this methodology was not used are described below. These were the segment definitions for the: pelvis; lower back; upper-back; head and neck; toes; and hands (Worthington, 2013).

4.4.1 Pelvis Segment

Due to a lack of markers defining a "longitudinal" axis of the pelvis and the longest axis being the sagittal axis, an xzy axis order was used to define the pelvis segment. The vector joining LASI and RASI was used as the first defining line, and the second defining line joined PELF and SACR (Section 4.3.2). The origin was positioned at the midpoint of the hip joint centres (Section 4.3.1).

4.4.2 Upper and Lower Back Segments

Upper and lower - back segments were defined using a zxy axis sequence; markers on the thorax did not allow the specification of a sagittal axis. Two virtual markers were defined for use in axis definitions:

FThorax = (CLAV + STRN) / 2

BThorax = (C7 + T10) / 2

The lower - back segment axes were positioned at LOWJC (see Section 4.3.2) and were defined using vectors joining SACR and the spinous process of L1 (LUM1), and LUM1 and STRN, as the first and second defining lines, respectively. Similarly, the origin for the upper-back was located at MIDJC, and was defined using vectors joining LUM1 and C7, and BThorax and FThorax (Worthington, 2013).

4.4.3 Head and Neck Segments

Four additional virtual markers were defined in order to specify the head and neck segment. Due to inaccuracies that were caused by variations in the position of the head markers from subject to subject, a head reference frame was defined (HeadRef). An xyz axis sequence was used and the defining lines: (RHead – LHead) and the global z-axis. HeadRef represented the head segment in the static trial using a coordinate system with its y - axis parallel to the ground. A temporary head and neck segment was also specified: (RHead – LHead) and (BHead – FHead) and an xzy axis sequence (equivalent to HeadRef once rotated about the x-axis). An offset between these two reference frames (HeadFlexOS) was calculated for each subject; enabling a corrected head and neck segment to be defined in the dynamic trials.

4.4.4 Toe and Hand Segments

A foot reference frame (FootRef) was defined to rotate the toe segments, to account for the TOE marker being positioned on top of the foot (Appendix 3). Using a static trial, with both feet flat on the ground, a virtual marker was defined for each foot (LRF and RRF, for the left and right feet respectively) with the x - and y - coordinates of the ankle joint centre and the z-coordinate of the MTP joint centre. FootRef was a foot segment with a z-axis parallel to the ground, defined using the virtual marker and the markers on the metatarsophalangeal (MTP) joint. The angle between FootRef and the toes segment was stored for each bowler (FootRefOS) and used to rotate the toe segment in bowling trials. In the same way, a correction was also applied to the hand segments using an offset calculated during the static trial in which subjects had their wrists straight.

4.5 Angle Definitions

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) in order to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using a xyz sequence representing an initial rotation about the x - axis of the parent, followed by the rotation about a floating y-axis of the parents and finally the z-axis of the child. These rotations corresponded to the flexion - extension, abduction -

adduction, and longitudinal rotation, respectively (Worthington et al., 2013). Positive angle changes and zero angle positions were defined as detailed in Table 4.1.

Table 4.1 – Details of the joint angles calculated.

Joint	+ve x	Anatomical Position	+ve y	Anatomical Position	+ve z	Anatomical Position
Shoulder	Flexion	0	Adduction	0	Internal Rotation	0
Elbow	Extension	180	Lateral Motion	0	Pronation	0
Wrist	Extension	180	Ulnar Flexion	0	Pronation	0
Trunk	Extension	0	Lateral Flexion (to the left hand side)	0	Trunk Rotation (to the right hand side)	0
Knee	Extension	0	Lateral Motion	0	Supination	0

4.6 Segmental Properties

The mass, position of the centre of mass and the three principal moments of inertia of each segment were defined using the output from the geometric model of Yeadon (1990) for each participant. The geometric model was customised to produce parameters for the eighteen segment representation developed for this study (Table 4.2). It was assumed the levels of the body defined by the geometric model of Yeadon (1990) were equivalent to the positions detailed on the next page:

Table 4.2 – Details of the assumptions made regarding the correspondence of the levels of the geometric model of Yeadon (1990) and the joint centres defined in this study (Worthington, 2013).

Yeadon's Level	Equivalent Level
Acromion	TOPJC
Lowest Front Rib	MIDJC
Umbillicus	LOWJC
Ball	MTP

To ease the implementation of segmental parameters determined using the geometric model of Yeadon (1990), additional segment coordinate systems were defined for each segment within the BodyLanguage code. These were identical to the segmental coordinate systems previously described, but with the origin relocated to the proximal joint of the segment. It was assumed the longitudinal axes of the segments (z-axis) defined within the BodyLanguage code corresponded exactly to those of Yeadon (1990). The longitudinal axis (z-axis) of each segment in the 18 segment system corresponded to the longitudinal axis in Yeadon's model.

This enabled the calculation of the motion of the whole body centre of mass for each participant. It was assumed that the centre of mass of the head and neck was located vertically above the joint centre (TOPJC) in the static trial. The adjusted segment axes enabled the position of the segment's centre of mass to be calculated in the dynamic trials (Worthington, 2013).

4.7 Data Reduction

The calculation of parameters describing aspects of badminton jump smash and tennis serve technique are explained in the following section. The parameters are defined in groups, according to the particular aspects of technique they correspond to.

4.7.1 Post Impact Speed

Curves were fitted separately to the pre - and post-impact phases of both the ball and shuttlecock in each of the three directions in accordance with Equation 1 (McErlain-Naylor et al., 2015).

$$b = \frac{1}{k} \cdot \ln(1 + k \cdot v_{\circ} \cdot t), \quad (1)$$

where b = displacement, t = time, k and v_0 are constants

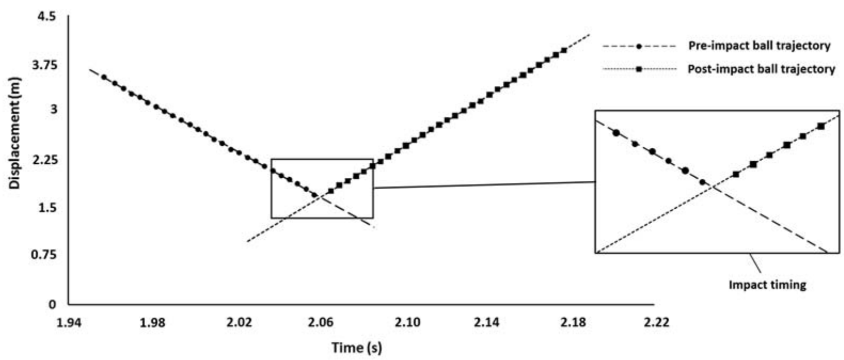


Figure 4.5 –Separate curves fit to the pre - and post-impact phases of shuttlecock position in one plane. Time of impact determined from the intersection of these curves (between raw data frames).

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilising a Trust - Region algorithm to determine values for k and v_0 (Figure 4.5). Time of impact was determined as the mean time at which the pre - and post-impact curves crossed in each plane, with differentiation of the three post-impact curves enabling the determination of the resultant instantaneous velocity at this time (McErlain-Naylor et al., 2015).

4.7.2 Kinematic Parameters

Kinematic parameters that have been either previously linked or thought to be linked to post impact speeds were calculated. Table 4.3 provides details on how each parameter was calculated for this study.

Table 4.3 – Details of angle calculations used in all studies.

Parameter	
knee flexion; prep	The x-axis of the when the dominate knee most flexed prior to take off.
trunk rotation; ER, RLP, BC	Overall Back z-axis at the key instants.
trunk extension; ER -BC	Max Overall Back x-axis angle between ER - BC phases.
trunk flexion; ER - BC	Min Overall Back x-axis angle between ER - BC.
trunk lateral flexion; max, ER- BC; RLP - BC	Maximum y-axis angle is at the between the ER - BC and RLP - BC phases.
shoulder external rotation; max, ER - BC	Min shoulder z-axis angle between ER - BC phases.
shoulder internal rotation; ER- BC; RLP - BC	Difference in z-axis between ER and BC key instant; RLP and BC phase.
shoulder abduction; ER - BC; RLP - BC	Difference in y-axis between the ER and BC Phase; RLP and BC key instant.
elbow extension angle; ER, RLP, BC	Calculated from the x-axis of the dominate elbow at the ER, RLP, and BC key instants.
elbow pronation; ER, RLP, BC	Calculated from the z-axis of the dominate elbow at the ER, RLP, and BC key instants.
elbow pronation; ER- BC: RLP - BC	The difference of the z-axis at the ER and BC key instants and RLP and BC key instants.
elbow pronation; max ER - BC	The max z-axis angle between ER-BC phases.
elbow pronation; min ER - BC	The min z-axis angle between ER-BC phases.
wrist extension; ER, RLP, BC	Calculated from the x-axis of the dominate wrist at the ER, RLP and BC key Instants.
timing; prep to BC	The difference of time between the Prep and BC key instants.
timing; prep to ER	The difference of time between the Prep and ER key instants.
timing; ER to BC	The difference of time between the ER and BC key instants.
timing; RLP to BC	The difference of time between RLP and BC key instants.

4.8 Statistical Analysis

All statistical analysis were performed in Statistical Package for Social Sciences v.22 (IBM Corporation, USA) the variations of speed observed were assessed using stepwise linear regression. Stepwise linear regression is a method of regressing multiple variables while simultaneously removing those that aren't important.

Forward stepwise regression designed to select from a group of predictors the one variable at each stage which has the largest semi-partial r-squared, and hence makes the largest contribution to R-squared. Predictors are stopped from being in the equation when no predictor makes a contribution which is statistically significant at a level specified by the user. With stepwise regressions only one independent variable is allowed for every five subjects (Tabachnick and Fidell, 1989). Therefore, within both the badminton jump smash and tennis serve studies the most predictive variables allowed for the regression model was three.

4.9 Chapter Summary

This chapter has described the 18 segment full - body analysis performed and provided details regarding the individual segment definitions. The combining of the subject - specific segmental parameters within the analysis was explained and details regarding the interpretation of the output parameters were provided. Calculations used to calculate descriptive variables for each trial were outlined and use of the value as a representative measure for each participant justified.

CHAPTER 5: OPTIMUM PERFORMANCE IN THE BADMINTON JUMP SMASH

5.1 Introduction

The badminton smash is an essential component of a player's repertoire and a significant stroke in gaining success as it is the most common winning shot, accounting for 53.9% of winning shots (Tsai et al., 1998; Tong and Hong, 2000; Rambely et al., 2005). The speed of the shuttlecock exceeds that of any other racket sport projectile with a maximum shuttle speed of 493 km/h (306 mph) reported in 2013 by Tan Boon Heong. If a player is able to cause the shuttle to travel at a higher velocity and give the opponent less reaction time to the shot, it would be expected that the smash would be a more effective weapon (Kollath, 1996; Sakurai and Ohtsuki, 2000).

There is limited research exploring the biomechanics involved in the badminton smash. However, research into other sports, involving motions very similar to the badminton smash (tennis serve, overarm throw) gives insight into the potential mechanisms involved in the badminton smash. Waddell and Gowitzke (2000); Lees (2002) and Lees et al. (2008) demonstrate that several biomechanical principles can be applied to the badminton smash such as increasing the range of motion of joint actions to allow a greater acceleration and more use of muscular force, the use of proximal - to - distal sequencing and the stretch - shortening cycle to improve performance and shuttle velocity.

It was originally thought that much of the velocity of the badminton smash was generated through what was termed the 'wrist snap' (palmar flexion). Much of the early research investigating power shots (clear and smash) in badminton used three-dimensional cinematography and relatively qualitative research methods. An early hypothesis, based on static photographs and self-analysis, suggested that velocity emanates from forearm pronation. The majority of the early research emphasised the importance of shoulder internal rotation and radio-ulnar pronation (Johnson and Hartung, 1974; Gowitzke and Waddell, 1977; Tang et al., 1995), whilst dismissing the contribution of palmer flexion (Poole, 1969, Gowitzke and Waddell, 1977 and Rantzmayer, 1977). Several studies aimed to quantify the contributions of specific joint movements and rotations to both the badminton smash and tennis serve. The majority of the findings indicated that internal shoulder rotation made the largest contribution (up to 66%) to shuttlecock velocity or racket-head speed in the badminton smash or tennis serve (Sprigings et al., 1994; Elliot et al., 1995; Lui et al., 2002; Tanabe and Ito, 2007).

Jumping while performing the smash is the most popular technique chosen by the world top ranked badminton players (Rambely et al., 2005). In the badminton smash, arm movement patterns have been shown to play an important role in the execution of the stroke (Ariff and Rambley, 2008). However, there has been some disagreement as to whether wrist action or forearm rotation is the best movement to generate racket head velocity. In previous research it has been found that the wrist played a major role in the forward swing mechanics of the racket. Since it gave velocity to the forehand smash, the contribution to linear racket head velocity was higher than those of the shoulder and elbow (Tsai et al., 2000). Previous research by Poole (1970) established that most of the velocity developed in overhead badminton stroking is a function of lower arm technique.

There is no consensus regarding which aspects of the badminton smash technique are the best indicators of shuttlecock velocity after impact. As has been described, a variety of different elements of technique have been reported to be linked to shuttlecock velocity by previous investigators. The purpose of this study was to identify the technique factors that contribute to players producing high shuttlecock velocities, with the aim of being able to inform coaches what to encourage in players when coaching, or recognise during the talent identification process.

5.2 Methodology

5.2.1 Participants

Eighteen male players (mean ± standard deviation: age 24.9 ± 6.5 years; height 1.84 ± 0.08 m; body mass 78.9 ± 9.0 kg) participated in this investigation. Each player performed twenty-four maximum velocity jump smashes which were recorded using an 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK), operating at 400

Hz. This was chosen based on previous overhead studies that used 400 Hz as cut-off to best capture the movement while tracking the most markers. The camera set-up was positioned to include the half of the court that the participant was performing in, approximately 7 x 6 x 3 m. All players were at least county standard up to members of the current England squad. No participants were aware of any injury/illness that would have affected their performance within the testing protocol. The testing procedures were explained to each participant in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All participants conducted a thorough warm-up prior to the start of the data collection.

5.2.2 Data Collection

Forty-four 14 mm retro-reflective markers were attached to each participant (Figure 5.1), positioned over bony landmarks. The players used their own racket for the data collection. Each racket was fitted with eight strips of reflective tape, plus a marker on the base of the racket (Figure 5.2) and Yonex AS40 shuttles were used with a strip of reflective tape attached to the base of the shuttle (Figure 5.2). Static and range of motion (ROM) trials were performed for each participant (Figure 5.2), allowing body segment lengths and a neutral spine position to be calculated (Ranson et al., 2008). Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990) enabling participant - specific segmental inertia parameters to be determined for each player.

Figure 5.1– Marker positions used in the badminton performance study.

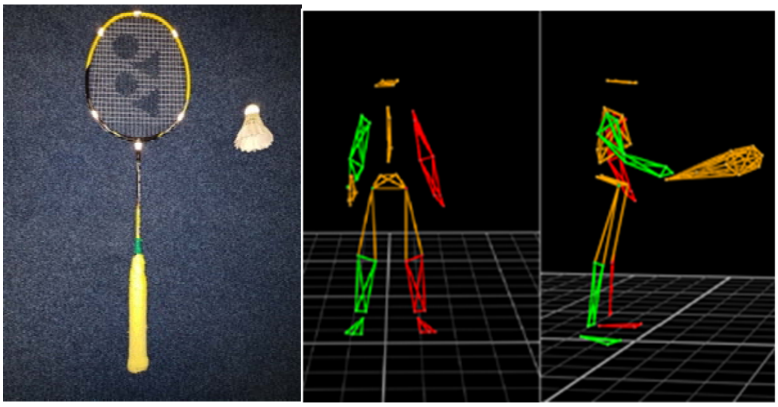


Figure 5.2 – The racket a position used in the badminton performance study and the static position of the participant.

5.2.3 Data Processing

The best trial with maximum velocity and minimal marker loss was identified for each participant. These trials were manually labelled and processed using the Vicon Workstation and BodyBuilder software (OMG Plc, Oxford, UK). For each trial four key instants were identified (Figure 5.3); the preparation (prep), end of retraction (ER), racket lowest point (RLP), and shuttle contact (SC). The instant of preparation was identified as when the knee angle was most flexed prior to jumping. The instant of ER was identified by the horizontal position of the racket behind the participant prior to the backswing. The instant of RLP was identified as the minimal vertical position of the racket prior to the forward swing of the racket. The instant of SC was identified as the frame where the shuttle and racket were closest. Kinematic data were filtered using a fourth order Butterworth filter (double–pass) with a low pass cut off frequency of 30 Hz.

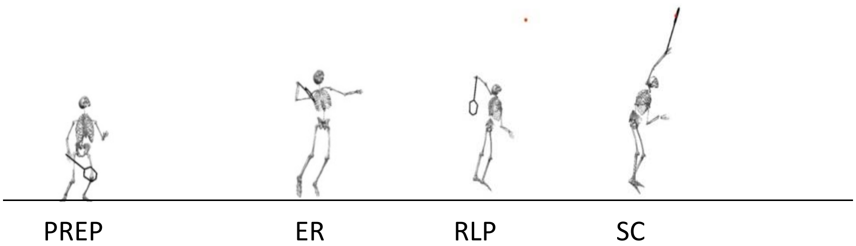


Figure 5.3 – Prep, ER, RLP, SC key instant of the badminton jump smash.

Joint centres were calculated from a pair of markers placed across each joint, positioned such that their mid-point coincided with the corresponding joint centre (Worthington et al., 2011). The hip joint centres were calculated using the 'hip joint centring algorithm' (Davis et al., 1991) from markers placed over the left and right anterior superior iliac spine and the left and right posterior super iliac spine. Lower and upper back motions were defined using the four markers on the pelvis in addition to markers placed over the proximal (sternal) and distal (clavicular) ends of the sternum as well as the spinous process of L1, T10, and C7 (Roosen, 2007).

Local reference frames were defined comprising a three – dimensional full body 18 segment representation of a player. These segments were head and neck; upper back; lower back; pelvis 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two segment foot. A local coordinate system was defined for each segment using three markers on the segment itself. This allowed segment orientations and joint angles to be calculated. The origin of each reference frame was located at the lower joint centre of the segment when the participant stood in the anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the participant's right (flexion - extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with the y-axis pointing forwards, the x-axis pointing to the right and the z-axis representing the upwards vertical.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) in order to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using a xyz sequence representing an initial rotation about the x-axis of the parent, followed by the rotation about a floating y-axis of the parents and finally the z-axis of the child. These rotations corresponded to the flexion - extension, abduction - adduction, and longitudinal rotation, respectively (Worthington, 2013).

5.2.4 Calculation of Shuttlecock Velocity

Curves were fitted separately to the pre- and post- impact phases of the shuttlecock in each of the three directions in accordance with Equation 1 (McErlain-Naylor et al., 2015).

$$b = \frac{1}{k} \cdot \ln(1 + k \cdot v_{\circ} \cdot t), \qquad (1)$$

where b = displacement, t = time, k and v_0 are constants.

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilising a Trust - Region algorithm to determine values for k and v_0. Time of impact was determined as the mean time at which the pre- and post- impact curves crossed in each plane, with differentiation of the three post-impact curves enabling the determination of the resultant instantaneous velocity at this time (McErlain-Naylor et al., 2015).

5.2.5 Statistical Analysis

Twenty-one parameters were calculated for each trial, describing elements of badminton smash technique which have previously been linked to shuttlecock velocity in literature or thought to be linked to shuttlecock velocity (Table 5.1). All statistical analysis was performed within Statistical Package for Social Sciences v 22 (IBM Corporation, US). The variations observed in each technique parameters were assessed using stepwise linear regression. A maximum of three variables were included in the predictive equation with the requirement for inclusion of a variable being $P < 0.05$.

5.3 Results

The eighteen badminton players participating in this study had shuttlecock velocity of 164 mph – 211 mph (194 mph ± 14 mph). Details of the range, mean, and standard deviation of each calculated technique parameter for the group of bowlers are provided in Table 5.1.

Table 5.1 – Details of the min, max, mean, and SD of each technique parameter calculated

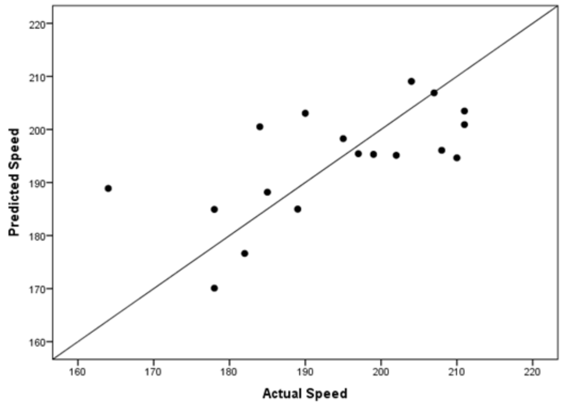
technique parameter	min	max	mean ± SD
shuttle velocity	164 mph	211 mph	195 ± 12 mph
knee flexion; prep	84°	136°	110 ± 12°
trunk rotation; ER	6°	33°	20 ± 8°
trunk rotation; SC	-10°	6°	-2 ± 5°
trunk extension; ER - SC	203°	233°	214 ± 7°
trunk flexion; ER - SC	165°	202°	183 ± 9°
trunk lateral flexion; max, ER - SC	-24°	3°	-12 ± 7°
shoulder external rot; max, ER - SC	105°	142°	122 ± 10°
shoulder internal rotation; ER - SC	-129°	-40°	-91 ± 24°
shoulder abduction; ER - SC	9°	39°	24 ± 8°
elbow extension angle; ER	54°	82°	65 ± 8°
elbow extension angle; SC	157°	174°	165 ± 5°
elbow pronation; ER	-111°	-35°	-81 ± 20°
elbow pronation; SC	-111°	-44°	-81 ± 18°
elbow pronation; ER - SC	-35°	35°	0 ± 18°
elbow pronation; max, ER - SC	-109°	-35°	-69 ± 20°
elbow pronation; min, ER - SC	-125°	-71°	-98 ± 14°
wrist extension; ER	255°	281°	270 ± 6°
wrist extension; SC	236°	268°	248 ± 10°
timing; prep to SC	0.22 s	0.70 s	0.58 ± 0.12 s
timing; Prep to ER	0.12 s	0.57 s	0.45 ± 0.11 s
timing; ER to SC	0.10 s	0.16 s	0.13 ± 0.01 s

Table 5.2 – Stepwise linear regression results for prediction of shuttlecock speed in the badminton jump smash.

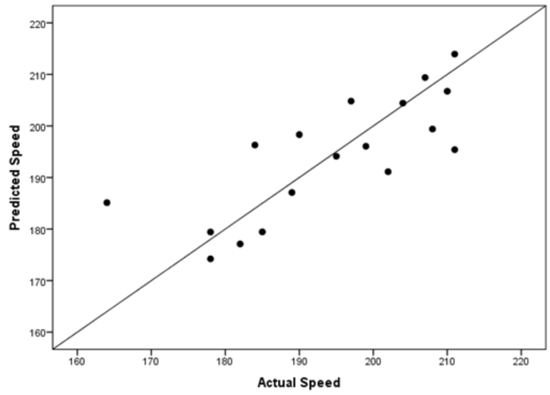
technique	coefficient	p-value	percent explained	lower bound	upper bound
elbow extension; ER	-1.266	0.001	51.5%	-1.92	-.615
elbow extension; ER	-1.419	0.000		-1.963	-.876
wrist extension; SC	0.607	0.009	69.9%	.179	1.036
elbow extension; ER	-1.357	0.000		-1.775	-.940
wrist extension; SC	0.632	0.001		.303	.960
timing; Prep-SC	43.118	0.004	83.7%	16.371	69.87

The best individual predictor of shuttlecock speed after impact was the elbow extension angle at ER, explaining 51.5% of the variation in shuttlecock speed. The badminton players with the fastest shuttlecock speed had a larger degree of elbow flexion at this instant in time. The use of two technique parameters in the predictive equation increased the percentage variation explained to 69.9%, those parameters being elbow extension angle at ER and wrist extension angle at SC. Adding timing from prep to SC to the first two variables gave a three - parameter function that explained 83.7% of variation in shuttle velocity (Table 5.2), (Figure 5.4).

(a) 1 parameter equation, 51.5%



(b) 2 parameter equation, 69.9%



(c) 3 parameter equation, 83.7%

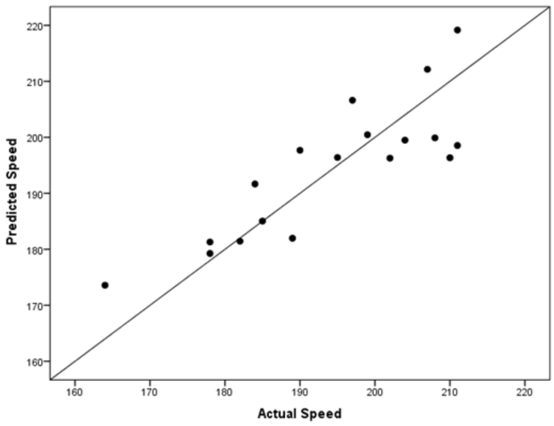


Figure 5.4 – Comparison of predicted and actual smash speeds for the three regression equations.

5.4 Discussion

Previous studies have reported correlations between shuttlecock velocity after impact and a variety of different elements of the badminton jump smash technique. There is currently no consensus as to which aspects of the technique are the most important in terms of determining shuttlecock jump smash. This study used stepwise linear regression in order to account for interactions between technique parameters with the aim of identifying the key variables that determine shuttlecock speed after impact. The results of this investigation suggest the main variations in shuttlecock speeds after impact among badminton players can be explained by using three technique parameters; elbow extension angle at ER, wrist extension angle at SC, and timing between prep and SC. The strongest predictor of smash speed was the elbow extension angle at ER with the badminton players with the faster smashes having a smaller elbow angle at ER than the slower ones. At the end of the retraction phase players are getting ready to bring their arm forward in a throwing type movement. Having a smaller elbow angle at this time gives a larger range of motion at the elbow prior to shuttle impact over which to generate speed, and also potentially puts the arm in a better position to use shoulder internal rotation to generate wrist and consequently racket and shuttle speed. For the first of these two it would be expected the smaller the elbow angle, the better as this will give a larger range of motion prior to shuttle impact. For the second mechanism it would be expected that an optimum elbow extension angle of around 90° exists as this gives the largest moment arm about the elbow to generate speed at the racket. A study by Tang et al., (1995) found the greater velocities of the racket head were produced by the elbow and wrist; and that these movements occurred immediately before shuttle contact and continued throughout contact.

There was a high degree of variability in the wrist angle at SC, but together with elbow extension angle at ER this helped explain 69.9% of the variability in shuttle speed. This emphasises that the wrist is clearly important for generating a high smashing speed and is in agreement with other studies in the literature (e.g. Tsai et al., 2000). The variability in wrist angle at SC makes it difficult to make specific recommendations around the optimal amount of wrist extension. The variability in this measure may in part be due to the identification of SC as the frame nearest to actual SC.

The predictive equation explaining the greatest percentage of variation observed in shuttlecock velocity (3 technique parameters), included the time from the start of the preparation phase through to shuttle contact along with both elbow extension angle at ER and wrist angle at SC. Longer times were found to be advantageous to greater shuttle speeds and this is probably in part due to a longer flight time prior to impact (due to a greater jump height) as well as a greater range of movement of the racket swing itself. Interestingly other more specific timings were not chosen for the stepwise linear regression.

For example, it might be expected that to a point a longer time between ER and SC would be advantageous to generating racket head and shuttle speed. This needs further investigation in the future and it may be that there is an optimum time to generate racket head speed which a more complex analysis could reveal.

Small sample sizes are a common problem when studying the populations in the current study. The data set of eighteen badminton players limited the number of technique parameters which could be confidently identified as explaining the variation in shuttlecock velocity to three. However, the 84% of variation in the shuttlecock velocity explained by the three parameter predictive equation suggests the key aspects of the technique have been identified.

The results of this study represent relationships between badminton jump smash technique and shuttlecock velocity among a group of eighteen badminton players, indicating the key aspects of technique which differentiated shuttlecock velocities within the group. Future studies should address the effect of changing aspects of technique on an individual. This would enable the effect of technique alteration to be addressed.

5.5 Conclusion

This study has identified three characteristics of the badminton jump smash technique which explain the majority of the variation in shuttlecock velocity after impact. Although there was quite a range of standard amongst the group of 18 players in this study from good county players to players competing internationally, it was possible to account for up to 84% of the variation in shuttle smash speed across the entire group. In particular, those players that had the fastest smashes had a relatively smaller elbow extension angle at the lowest vertical position of the racket in the backswing, an appropriate wrist extension angle at shuttle contact and a relatively longer time between the start of the jump smash movement. Although further work is needed to full understand why some players can smash the shuttle faster than others this investigation provides a basis for further study. The key parameters identified in this study results can be useful in the coaching of the badminton jump smash.

CHAPTER 6: VARABILITY IN THE BADMINTON JUMP SMASH

6.1 Introduction

Badminton is a game of quick movements and quick reactions (Kwan, 2010) the smash is the most powerful stroke of all. The badminton smash is known as the most powerful stroke because of its speed and steep trajectory which contributes to a winning point (Ariff and Rambley, 2008). The smash is also defined as the most common killing shot, is accounted for 53.9% of the distribution of the killing shots (Tong and Hong, 2000). Due to a high requirement of athletes' physical exertion, such as speed, power, smash precision, flexibility and coordination, the skill is always a challenge for players to accomplish with a high quality (Li et al., 2016). In order to be successful at badminton, a player must be able to hit the smash accurately and consistently during their match. High speeds and accuracy are two components of the badminton smash that a player needs to master in order to be successful.

Despite a long history of research describing movement variability and its functional relevance to human movement (Hatze, 1986; Winter, 1984) variability in sporting motions was often considered noise (Barlett et al., 2007). Research into how variability may affect the badminton smash technique or velocity of the shuttlecock has been limited. A study done by (Antunez et al., 2012) found that consistency in speed and location of the tennis serving hand around impact is positively related to serve speed and accuracy. The speed of a tennis serve was an important criterion of the serve performance. An increasing serve speed reduces the time for the opponents to prepare to return the ball successfully and increases the chances of the server winning the point (Vaverka and Cernosek, 2016). The same can be said for the badminton smash. Players tend to hit the smash towards the body of their opponent in order to reduce the chances of their opponent returning the smash. Research into the baseball pitch suggests that variability in timing may actually be desirable for improved performance. One explanation might be because variability protects against possible injury. A 2013 study by Tucker et al. found that there was no relationship between performance variability and outcome variability in the golf swing.

In a badminton jump smash the two critical outcome variables are the speed of the shuttle and the vertical downward direction of the shuttle after impact. Currently there is no consensus regarding variability and how it affects the badminton smash speed or the downward direction of the shuttle after impact. The aim of the current study was therefore to identify how consistent a badminton player was in their smash technique and the effects on shuttle speed and vertical angle.

6.2 Methodology

6.2.1 Participants

Three female (mean ± standard deviation: age 20.1 ± 0.4 years; height 1.67 ± 0.03 m; body mass 64.5 ± 5.4 kg) and six male players (mean ± standard deviation: age 29.1 ± 7.1 years; height 1.77 ± 0.07 m; body mass 79.0 ± 7.9 kg) participated in this investigation. Each player performed twenty-four maximum velocity jump smashes which were recorded using an 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK), operating at 400 Hz. The camera set-up was positioned to include the half of the court that the participant was performing in, approximately 7 x 6 x 3 m. All players were at least county standard up to members of the current England squad. No participants were aware of any injury/illness that would have affected their performance within the testing protocol. The testing procedures were explained to each participant in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All participants conducted a thorough warm-up prior to the start of the data collection.

6.2.2 Data Collection

Forty-four 14 mm retro-reflective markers were attached to each participant (Figure 6.1), positioned over bony landmarks. The players used their own racket for the data collection. Each racket were fitted with seven strips of reflective tape, plus a marker on the base of the racket (Figure 6.2) Yonex AS40 shuttles were used with a strip of reflective tape attached to the base of the shuttle (Figure 6.2). Static and range of motion (ROM) trials were performed for each participant (Figure 6.2), allowing body segment lengths and a neutral spine position to be calculated (Ranson et al., 2008). Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990) enabling participant-specific segmental inertia parameters to be determined for each player.

Figure 6.1–Marker positions use on the body in the badminton variability study.

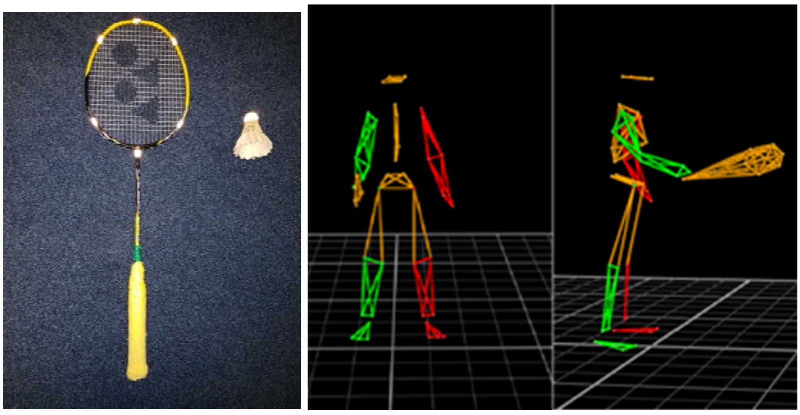


Figure 6.2 – Marker positions used in the badminton variability and the static position of participant.

An experienced coach with international playing experience served the shuttlecock from the opposite side of the court (Figure 6.3). A life size target in a defense stance was used as a target and participants were asked to aim for the same spot on the target for each smash while hitting the shuttle as hard and as accurately as they could.

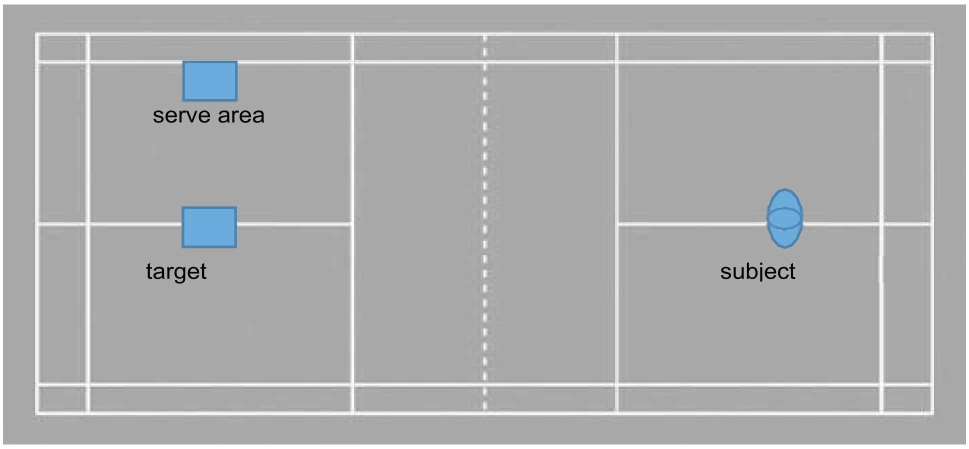


Figure 6.3 – The data collection set–up for the badminton variability study.

6.2.3 Data Processing

The best twelve trials with maximum velocity and minimal marker loss, was identified for each participant. These trials were manually labelled and processed using the Vicon Nexus and BodyBuilder software (OMG Plc, Oxford, UK). For each trial four key instants were identified (Figure 6.4): the preparation (prep); end of retraction (ER); racket lowest point (RLP);and shuttle contact (SC). The instant of preparation was identified as when the knee angle was most flexed prior to jumping. The instant of ER was identified by the maximum horizontal position of the racket behind the participant prior to the forward swing of the racket. The instant of RLP was identified as the minimal vertical position of the racket prior to the forward swing of the racket. The instant of SC was identified as the frame where the shuttle and racket were closest. Kinematic data were filtered using a fourth order Butterworth filter (double-pass) with a low pass cut off frequency of 30 Hz as determined by a residual analysis (Winter, 1990).

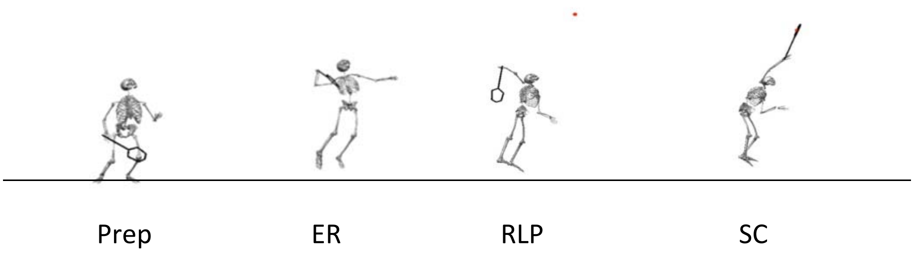


Figure 6.4 – The Prep, ER, RLP, and SC key instants of the badminton smash.

6.2.4 Joint Calculations

Joint centres were calculated from a pair of markers placed across each joint, positioned such that their mid-point coincided with the corresponding joint centre (Worthington et al., 2013). The hip joint centres were calculated using the 'hip joint centring algorithm' (Davis et al., 1991) from markers placed over the left and right anterior superior iliac spine and the left and right posterior super iliac spine. Lower and upper back motions were defined using the four markers on the pelvis in addition to markers placed over the proximal (sternal) and distal (clavicular) ends of the sternum as well as the spinous process of L1, T10, and C7 (Roosen, 2007).

Local reference frames were defined comprising a three-dimensional full body 18 segment representation of a player. These segments were: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two segment foot. A local coordinate system was defined for each segment using three markers on the segment itself. This allowed segment orientations and joint angles to be calculated. The origin of each reference frame was located at the lower joint centre of the segment when the participant stood in the anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the participant's right (flexion-extension axis of the joint) and the y-axis pointed forward similarly, a global coordinate system was defined with the y-axis pointing forwards, the x-axis pointing to the right and the z-axis representing the upwards vertical.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) in order to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using a xyz sequence representing an initial rotation about the x-axis of the parent, followed by the rotation about a floating y-axis of the parents and finally the z-axis of the child. These rotations corresponded to the flexion-extension, abduction-adduction, and longitudinal rotation, respectively (Worthington et al., 2013).

Angles measured about the x- axis correspond to the flexion and extension angle of the joint. In an anatomical position the shoulder, elbow, and wrist are 180°, 180° and 0° respectively. The trunk flexion/extension angle (also measured about the x-axis) was normalised using a neutral position of the spine determined from the static trial taken, which is set at 0° (Worthington et al., 2013). Angles in the y-axis measuring lateral motion (adduction/abduction and trunk lateral flexion). In an anatomical position the shoulder joint is 180° and the trunk is normalised using the static trial neutral position, the same as the x-axis. The z-axis relates to the trunk rotation (twist) about the longitudinal axis of the segment. In an anatomical position of the shoulder, elbow, and wrist joints are all at 0°. The trunk segment follows the same principle as the x and y axes, set at 0° when normalised using the static trial.

6.2.5 Calculation of Shuttlecock Velocity and Vertical Downward Angle

Curves were fitted separately to the pre- and post- impact phases of the shutlle in each of the three directions with accordance to Equation 1 (McErlain-Naylor et al., 2015).

$$b = \frac{1}{k} \cdot \ln(1 + k \cdot v_{\circ} \cdot t), \quad (1)$$

where *b* = displacement, *t* = time, *k* and v_0 are constants.

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilising a Trust-Region algorithm to determine values for k and v_0. Time of impact was determined as the mean time at which the pre- and post-impact curves crossed in each plane, with differentiation of the three post-impact curves enabling the determination of the resultant instantaneous velocity at this time (McErlain-Naylor et al., 2015).

The calculations of the vertical downward angle after impact and the horizontal angle were calculated from the post-impact curves of the shuttle and the markers on the racket head using the code written by McErlain-Naylor et al. (2015).

The direction of the shuttlecock was defined by the vertical angle. The vertical angle was defined as the downward angle between the direction of the shuttlecock and the horizontal (Figure 6.5). The horizontal angle which was defined as the angle between the direction of the shuttlecock and the centre line of the court was also found. However, due to the high level of variability within the data for the angle it was not examined in this study.

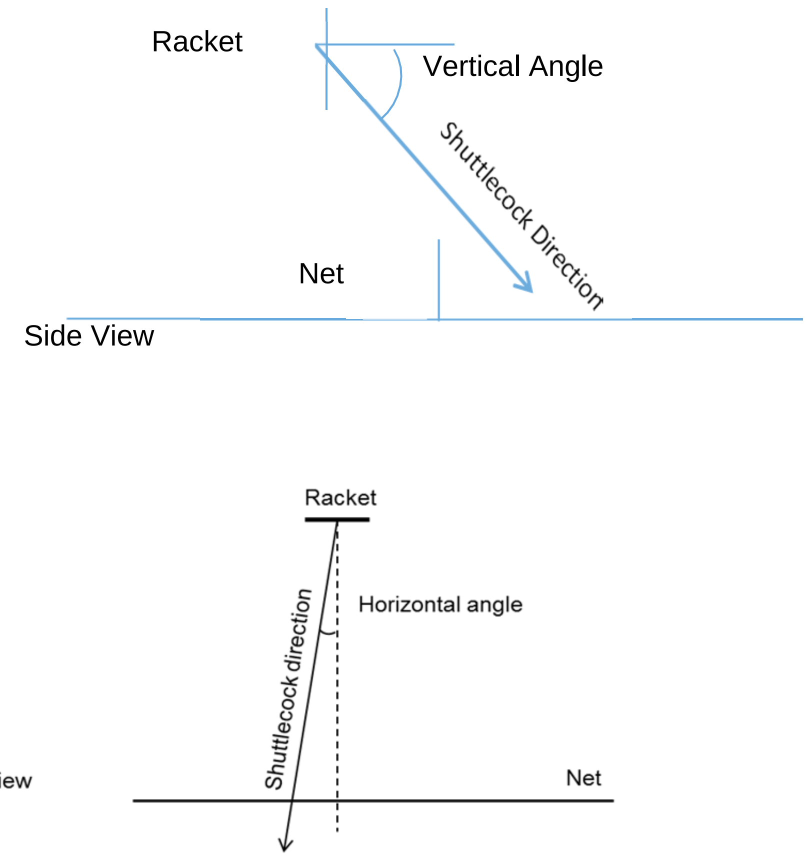


Figure 6.5 – The definition of vertical downward and the definition of horizontal angle.

6.2.6 Shuttlecock Location

The shuttlecock location at impact was calculated using the x direction and y direction of the shuttlecock at impact relative to the racket. Shuttlecock location at impact relative to the toe at take-off was calculated by taking the difference of the x direction and y direction of shuttle at impact and the toe at take-off and finding the values. The shuttlecock location at three metres high was taken from the x and y direction of the shuttlecock relative to the global coordinates of the floor.

6.2.7 Analysis

Initially mean and variability (standard deviation) were calculated for speed and vertical angle for each subject. The shuttlecock location at three meters high prior to impact and the shuttlecock location at impact relative to the toe at take-off was also found for each player.

6.2.8 Statistical Analysis

One-way ANOVA tests were performed within SPSS v22 (IBM Corporation, USA) to identify any significant differences in speed, shuttlecock location at three meters high, shuttlecock location relative to toe at take-off, and timings within the group.

6.2.9 Data Reduction

Out of nine participants, three were chosen to be analysed in more detailed. The variability of the shuttlecock speed of participant 5 was considerably higher than the rest of the group (Table 6.1). Therefore he was chosen as the least consistent player. The shuttlecock speed of participant 2 had a lower variability than all other participants and was chosen as the most consistent player in the study while participant 6 had an average speed that was between P2 and P5 and a variability that was in the middle of the group. For the three participants' knee, elbow, wrist, and shoulder data were compared.

6.3 Results

Speed

The nine badminton players participating in this study had a shuttlecock speed range of 147 – 220 mph (Table 6.1). The average speed for the entire group was 194 mph.

Table 6.1 – Min, max, mean and standard deviation of speed for each player in badminton jump smash.

subject	min (mph)	max (mph)	mean (SD %)*
Males			
1	189	225	213 ± 4%
3	189	211	201 ± 4%
4	182	202	195 ± 4%
5	179	220	207 ± 8%
6	182	202	193 ± 4%
9	200	235	218 ± 5%
Females			
2	180	196	186 ± 3%
7	166	188	176 ± 4%
8	147	168	159 ± 4%

*SD was calculated as a percentage of the average speed per player.

The data showed that variability (standard deviation) of the female badminton players tended to be similar than that of the male players. However, the females did not reach the same speeds as the male players.

Vertical Angle

The nine badminton players participating in this study had a vertical angle range of -21° to -8°. The vertical angle for all participants was similar. Participant 4 had the highest SD of all the participants. Male participants tended to have the steepest vertical downward angle than the females (Table 6.2).

Table 6.2 – Min. max, mean and standard deviation of vertical angle for each player in the badminton jump smash.

subject	min (°)	max (°)	mean (SD)
Males			
1	-15	-10	-12 ± 1
3	-16	-10	-13 ± 2
4	-19	-9	-14 ± 3
5	-20	-15	-17 ± 2
6	-16	-12	-14 ± 1
9	-21	-14	-17 ± 2
Females			
2	-14	-8	-11 ± 1
7	-15	-9	-12 ± 2
8	-15	-8	-11 ± 2

Shuttle Location

It was the goal of the server to serve the shuttlecock consistently throughout the data collection. One–way ANOVA tests showed that there was no significant difference between the subjects in the x-direction $F (8, 99) = 1.44$, p .190. The ANOVA showed that there was a significant difference for the shuttle location at three metres high in the y - direction $F (8, 99) = 5.33$ $p = .000$ A closer analyses with a post hoc Tukey test showed that the differences was because a small group of participants were significantly different to each other (Table 6.3; Figure 6.6).

Table 6.3 – One–way ANOVA regressions highlighting difference of shuttle location at three metres high between players.

Participant A	Participant B	Significant Difference
2	7	.012
4	8	.000
4	9	.042
7	8	.000
7	9	.006

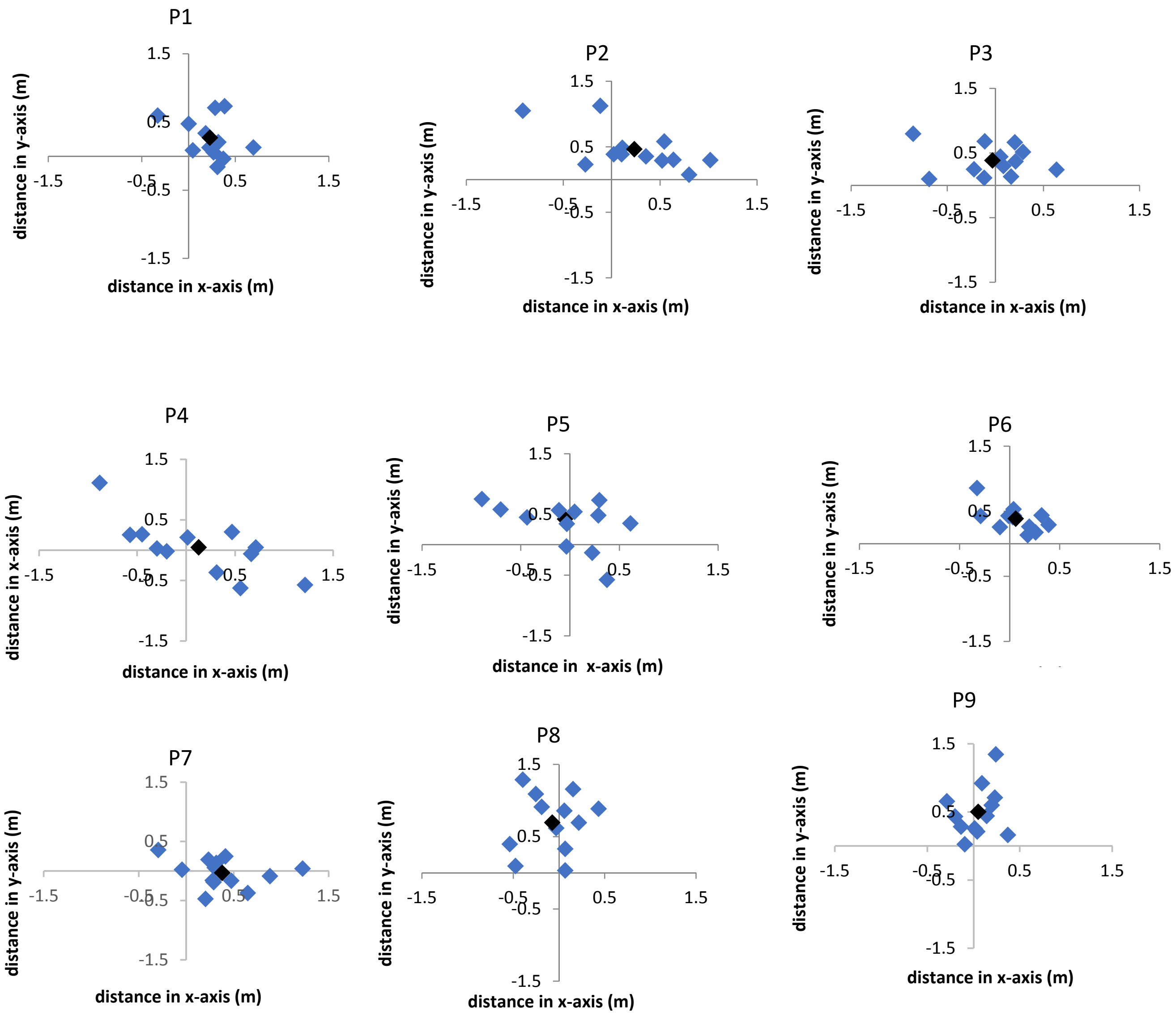


Figure 6.6 – Shuttlecock location at three metres high relative to the court prior to impact with the mean is in black.

One-way ANOVA tests showed that there were significant differences between the groups in both the x direction, F (8, 99) = 6.824 p>0.000 and in the y direction (F (8, 99) = 14.750 p>0.000 in the shuttle location at impact relative to the toe at take-off (Figure 6.7). This could be because of the different positions that the players take in order to prepare for the badminton jump smash.

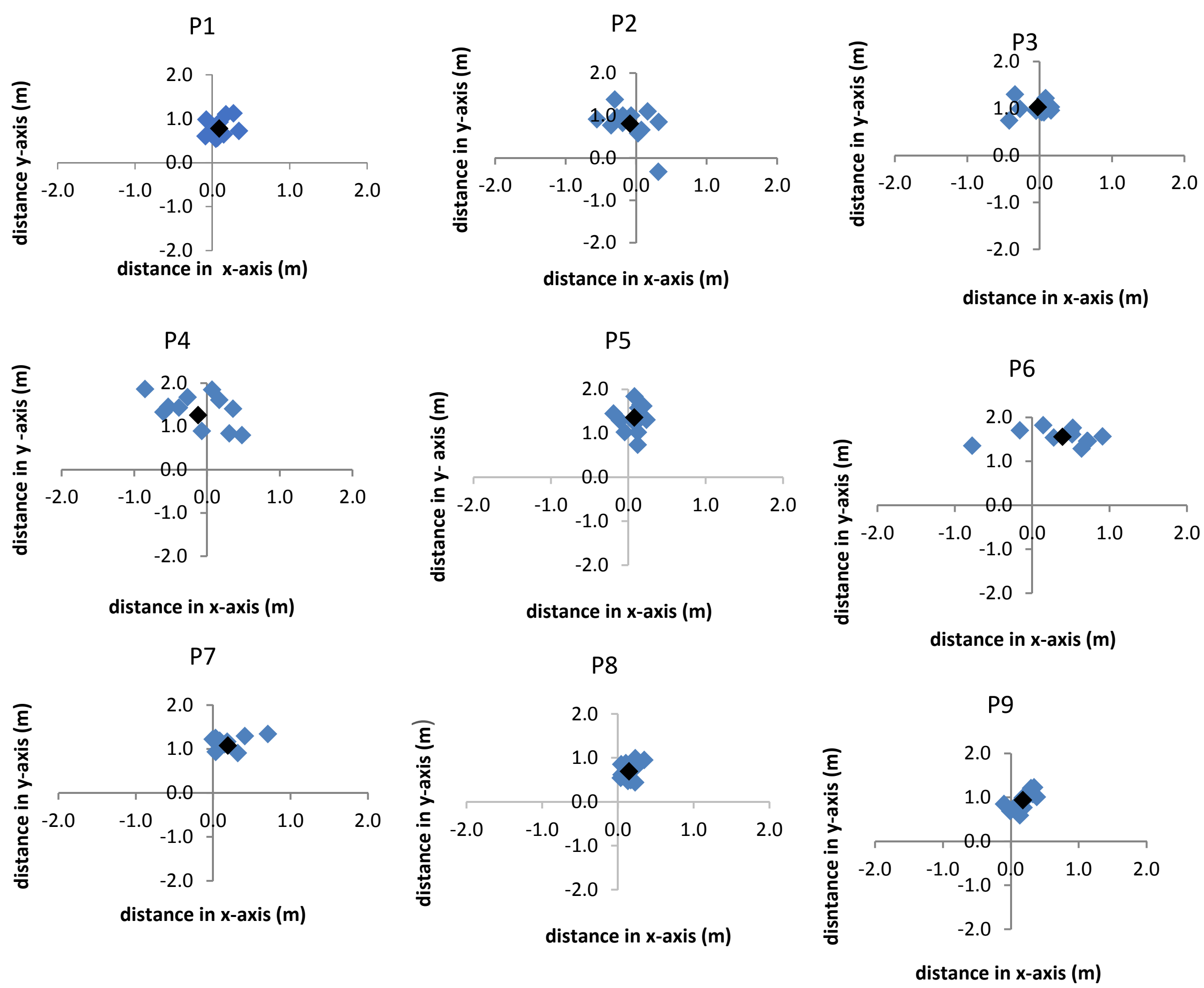


Figure 6.7 – Shuttlecock location at impact relative to toe at take-off with the mean in black.

Shuttle Location on the Racket at Impact

Across the group the data showed that participants tended to hit the shuttlecock within a cluster on the racket (Figure 6.8). The three players chosen for comparisons are highlighted in green. Out of our three participants, P5 showed to have the most variability of shuttle location on the racket at impact. Meanwhile, P2 had the smallest and P6 was in the middle.

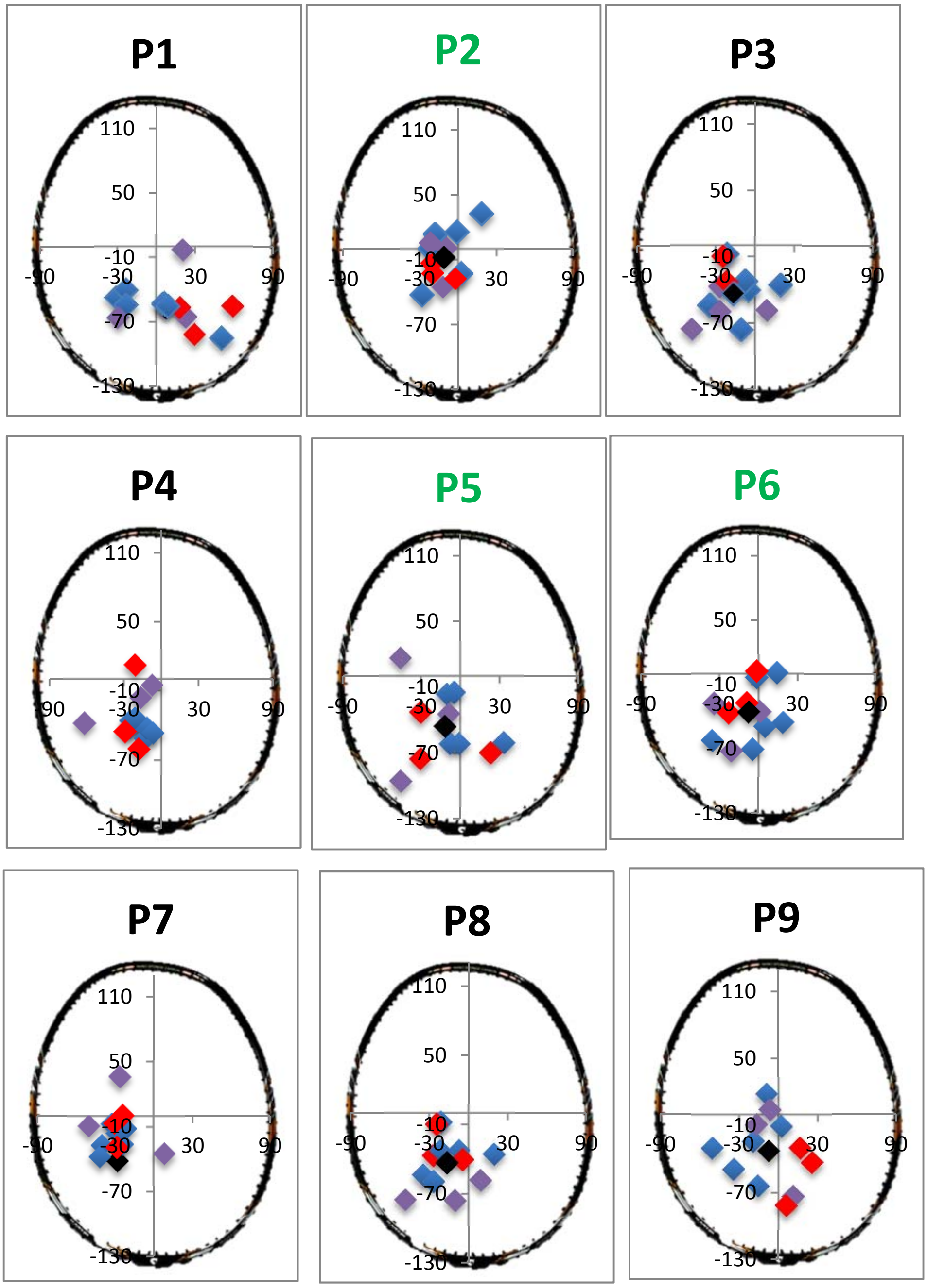


Figure 6.8 – Shuttle location on the racket at impact for all plotted trials. The three fastest trials are represented in red while the three slowest trials are represented in purple and the mean is represented in black.

Comparison of Three Participants of the Badminton Jump Smash

Three participants (P2, P5, and P6) were chosen to be analysed more in depth. The three participants were chosen based on their degree of variability. The One-way ANOVA test showed that there was no significant difference in shuttle location at three metres high, reflecting the coach's ability to serve the shuttlecock consistently for these three participants. Therefore, any difference would be down to the player's technique.

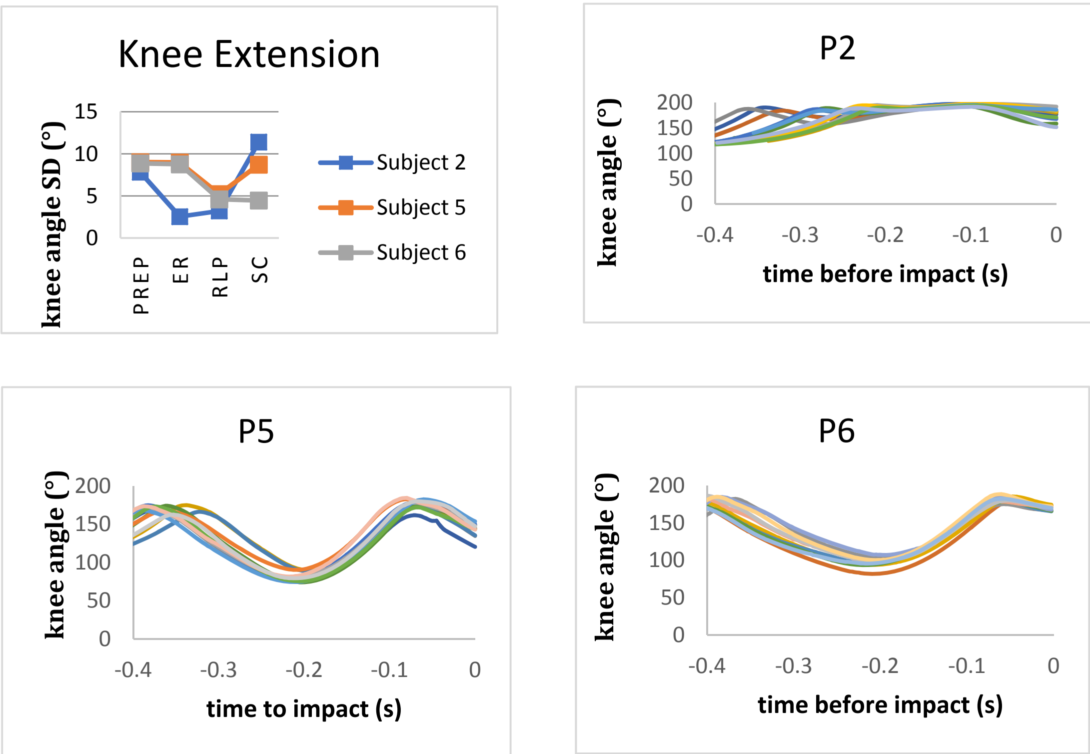


Figure 6.9 – SD of knee extension and flexion through the key instants (top left); knee extension and flexion of all trials plotted.

Examination of the variability data for the knee extension reveals that participants P5 and P6 both flexed their knees prior to take off and again in mid-air prior to shuttle contact (Figure 6.9). Participant P2 tended to flex the knee prior to take-off however the knee remained static throughout the rest of the jump smash. P5 (145°) had a lower average knee angle than P2 (171°) and P6 (150°).

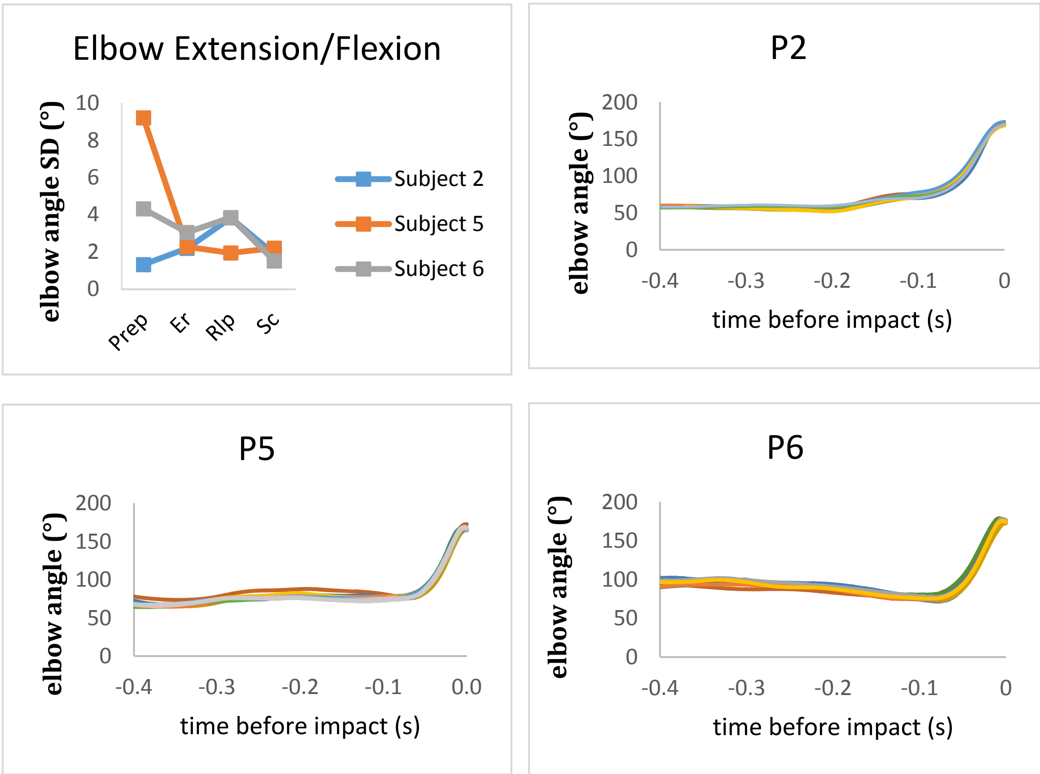


Figure 6.10 – SD of elbow extension and flexion through the key instants (top left); elbow extension and flexion of all trials plotted.

Examination of the variability data for the elbow flexion and extension angle reveals that there was a similar pattern between the three participants although P6 (21°) had a higher variability than P2 (17°) and P5 (15°). During the jump smash action, the elbow remained relatively static throughout before extending though the motion (Figure 6.10). Participants P5 and P6 tended to extend a little later in the smash compared to subject P2.

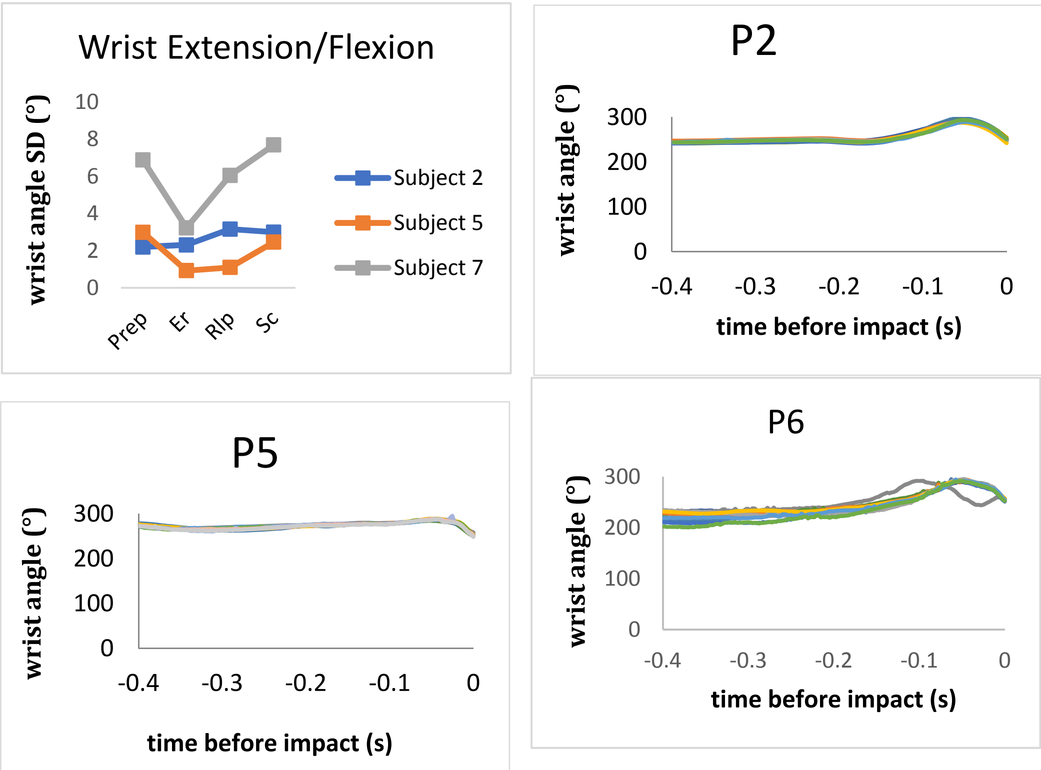


Figure 6.11 – SD of wrist extension and flexion through the key instants (top left); wrist extension and flexion of all trials plotted.

Examination of the variability data for the wrist extension and flexion angle (Figure 6.11) reveals similar trends among the participants, although in participants P2 and P6 the wrist extended before flexing while in P5, the wrist remained static before flexing. The shape was similar for all participants with the wrist extending before flexing within the jump smash. The average angle for the wrist was also higher in P5 (274°) compared to P2 (256°) and P6 (256°).

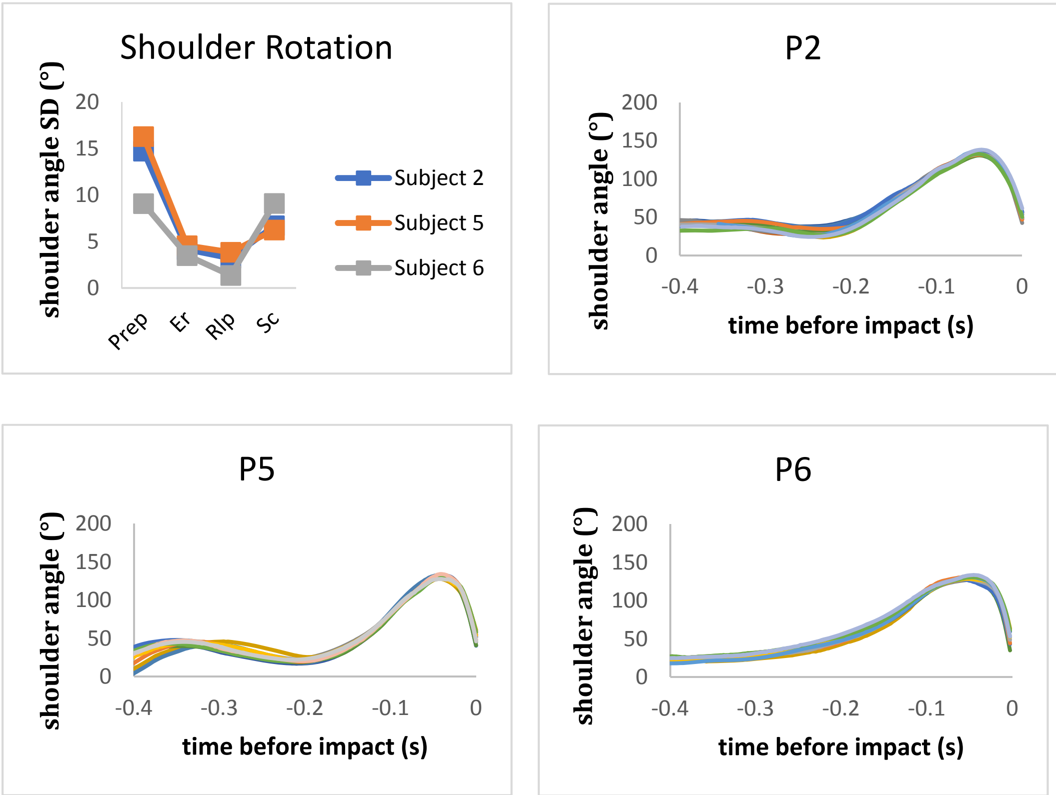


Figure 6.12 – SD of shoulder rotation through the key instants (top left); shoulder rotation of all trials plotted.

The variability for shoulder rotation throughout the jump smash showed that P6 had a higher variability than P2 or P5. The data shows that S5 started internal shoulder rotation before P2 and P6. P2 (72°) had a higher average of shoulder rotation angle than that of P5 (53°) and P6 (63°).

The ANOVA test between the three participants showed that there was a significant difference for the ER - SC phase, ($F\ (2, 33) = 86.387$, $p<0\ .000$).

Table 6.4 – The timings of key instants for badminton jump smash.

	Prep-ER (SD)	**Prep-SC(SD)**	**ER-SC(SD)**
P2	0.44 (0.23)	0.57 (0.23)	0.13 (0.00)
P5	0.43 (0.07)	0.54 (0.07)	0.11 (0.00)
P6	0.45 (0.06)	0.57 (0.06)	0.12 (0.00)

6.4 Discussion

The purpose of this study was to examine movement variability in the badminton jump smash. A number of differences in technique, speed, and movement timings have been identified. Variability data for four kinematic variables for three participants of varying degrees of speed variability was examined in further detail.

The shuttlecock speed of all participants ranged from 147 mph – 236 mph. A previous study have reported slower speeds in the badminton jump smash (Tsai et al., 1998) however; this is most likely due to the lower frequency (120 Hz) used in the data collection for the study.

Although the ANOVA test showed that there was a significant difference in x and y direction for the shuttlecock at three metres high prior to impact, when analysing the results more closely it was shown that the significant difference was caused by three players being different from one another. Although the coach strived to serve the shuttlecock in the same manner throughout the data collection process inevitably human error may come into play at some point.

The three participants that were chosen for further analysis showed that for them there was no significant difference in their shuttlecock serve. Any differences shown with the analysis of the data would be a result of the participants' technique and not due to the coach serve of the shuttlecock. This can be seen as soon as the participants prepare for take-off before impact. The significant difference reflected in the analysis could be because of the different approaches that the participants took into order to position the body in order to perform the jump smash. Upon inspection of the data it could be seen that some participants tended to move their feet more than others when preparing to perform the smash.

Three participants were chosen for further analysis based on their variability in terms of shuttlecock speeds post impact. Analysis of the data showed that for the three participants there were also differences in shuttle location on the racket at impact. All subjects were asked to hit the shuttlecock as hard and as accurately as they could. The less consistent participant had a more off centre placement of the shuttle at the impact compared to the other two participants. This could account for some of the variation in post impact speed that the participant had. Another possibility that may account for the variation in speeds between our three participants is the speed - accuracy trade-off. While the less consistent participant 5 may have decided to hit the shuttlecock as hard as he could regardless of the accuracy, the more consistent and average consistent participants may have decided to sacrifice speed in order to be more accurate in their jump smash placement.

The data showed that the female participants tended to have a straighter knee throughout the jump smash compared to the male participants. The male participants also tended to flex their knee mid-jump prior to impact, while the females did not. The bending of the knee in mid-jump allows for a participant to rotate more at the torso and therefore transferring more energy to the upper segments of the body for a harder hit.

All participants had a similar pattern for elbow extension and flexion throughout the jump smash, however the more consistent player tended to extend the elbow before flexing it prior to impact. Wrist extension and flexion data showed that the participants who had average consistency and more consistency in speeds in their smash extended their wrist before flexing it prior to impact. The less consistent player remained static throughout the smash before flexing the wrist.

Although all participants had a similar pattern in shoulder rotation during the jump smash the participant with average consistency remained static prior to rotating their shoulder compared to the less consistent and more consistent participants.

The movement timings between the players showed significant differences between the participants in the ER – SC phase. It is interesting that the participant with the lowest consistency in smash speeds had the fastest times during this phase. It could be said that longer times within these phases allows for a participant to judge the shuttle better, therefore getting in a better position to hit the smash harder.

When looking at the difference in the subject details (Appendix 1) we see that participant

2 in shorter than that of participant 5 and participant 6. The additional height for these two players can provide them with a greater downward angle when they are attempting the badminton jump smash. By having a steeper angle this can help the player have a longer amount of time to rotate their shoulder, thus proving more momentum for the speed needed to complete the jump smash.

6.5 Conclusion

This study has investigated movement variability among elite badminton jump smash players. Differences in body placement, shuttle location on the racket at impact, and movement timings could be identified for all players. Differences in variability between a less consistent, average, and more consistent player have been identified. The findings in this study can be useful in the coaching of the badminton jump smash. Coaches can teach their players that a flexed leg mid-jump could better help them produce the energy needed for a fast jump smash. Although further work is needed to understand the full extent of movement variability and speed trade off this investigation provides a basis for further study. Also, by seeing the effects of the speed-accuracy trade-off coaches can better train their athletes to reach their maximum speed without sacrificing accuracy. While each player may have their own 'sweet spot' in terms of shuttle placement on the racket at impact, the data shows that for the majority it is better to hit nearer towards the racket centre. This can allow coaches to focus on racket placement during training sessions. By applying the results in a practical manner to their players, coaches can help their athletes in perfecting their jump smash technique.

CHAPTER 7: RELATIONSHIP BETWEEN DIRECTION, TECHNIQUE AND SPEED IN THE TENNIS SERVE

7.1 Introduction

In tennis, the serve is one of the most difficult strokes to master even though it is directly under the control of the player (Chow et al., 2003). The serve is a key element of a tennis match, with the player having the opportunity to markedly influence the subsequent strokes in the point (Vaverka, 2012). Since the service starts every point, increasing the speed of the serve is a key part of developing a more competitive tennis game. The success of a serve depends on the speed, control, and spin of the ball (Tanabe, 2007). For this reason it is important to understand the elements that contribute to both speed and accuracy in the tennis serve. Especially important is speed of the ball after impact, so speed of the racket at impact is central to a successful serve.

The coordination of the body segments occur in a sequence referred to as the 'kinetic chain' (Braden and Bruns 1977; Elliott and Kilderry 1983) so that an optimal racket position, trajectory and speed are apparent at impact. The kinetic chain is a series of motions that start from the ground and goes to the racket. Once an effective swing has been developed, the server must integrate movement of the lower limbs into the action to drive the body upward and forward for impact. The lower limb drive not only begins the drive to the ball but also assists in increasing the range of racket movement during the loop of the racket behind the player's back.

Bruce Elliott (1995) has stated that trunk and leg rotation are important in powerful hitting movements such as hockey penalty stroke and baseball batting. The same importance can be shown with the tennis serve. Moreover, Bagamonde reported a relationship between trunk rotation and racket speed and stated that one of the most important elements of the forehand and backhand strokes was the development of optimal trunk rotation and that trunk rotation was highly correlated with racket speed. A precise coordination of the upper extremity is necessary for attaining a high speed performance outcome. Among the joint rotations involved in the tennis serve, rapid shoulder internal rotation is known to contribute greatly to produce a high speed serve.

7.2 Methodology

7.2.1 Participants

Seventeen male players (mean ± standard deviation: age 19.8 ± 2.3 years; height 1.83 ± 0.05 m; body mass 75.3 ± 7.3 kg) participated in this investigation. Each player performed forty tennis serves which were recorded using an 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK), operating at 400 Hz. The camera set-up was positioned to include the half of the court that the participant was performing in, approximately 7 x 6 x 3 m. All players were at least county standard. No participants were aware of any injury/illness that would have affected their performance within the testing protocol. The testing procedures were explained to each participant in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All participants conducted a thorough warm-up prior to the start of the data collection.

7.2.2 Data Collection

Forty-four 14 mm retro-reflective markers were attached to each participant (Figure 7.1), positioned over bony landmarks. The players used their own racket for the data collection. Each racket was fitted with seven strips of reflective tape, plus a marker on the base of the racket (Figure 7.2) and new Wilson tennis balls were used with a six strips of reflective tape attached to the ball (Figure 7.2). Static and range of motion (ROM) trials were performed for each participant (Figure 7.2), allowing body segment lengths and a neutral spine position to be calculated (Ranson et al., 2008). Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990) enabling participant-specific segmental inertia parameters to be determined for each player.

Figure 7.1 – The marker positions on the body used in the tennis study.

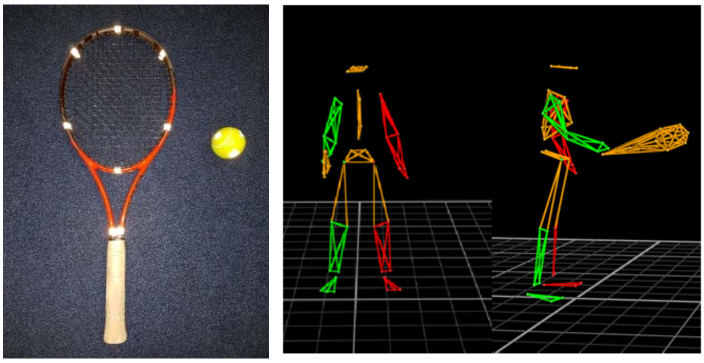


Figure 7.2 – The marker positions used on the tennis racket and ball; static position of participant in the tennis study.

7.2.3 Data Processing

The best trial with maximum speed and minimal marker loss, in each of the four directions of the tennis service court (deuce court, advantage court, right centre, and left centre) was identified for each participant (Figure 7.3). These trials were manually labelled and processed using the Vicon Workstation and BodyBuilder software (OMG Plc, Oxford, UK). For each trial four key instants were identified (Figure 7.4); the preparation (prep); end of retraction (ER); racket lowest point (RLP); and ball contact (BC). The instant of preparation was identified as when the knee angle was most flexed prior to jumping. The instant of ER was identified by the horizontal position of the racket behind the participant prior to the forward swing. The instant of RLP was identified as the minimal vertical position of the racket prior to the forward swing of the racket. The instant of BC was identified as the frame where the ball and racket were closest. Kinematic data were filtered using a fourth order Butterworth filter (double – pass) with a low pass cut off frequency of 30 Hz.

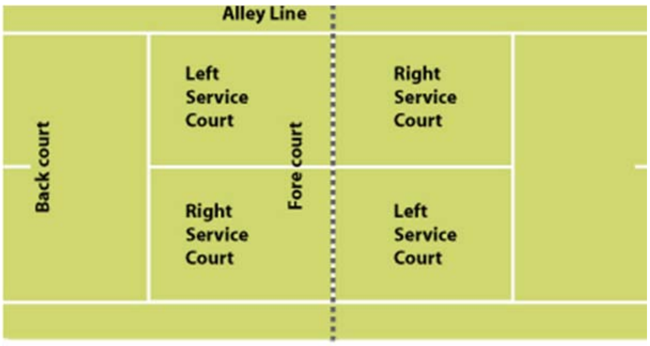


Figure 7.3 – The tennis court service area.

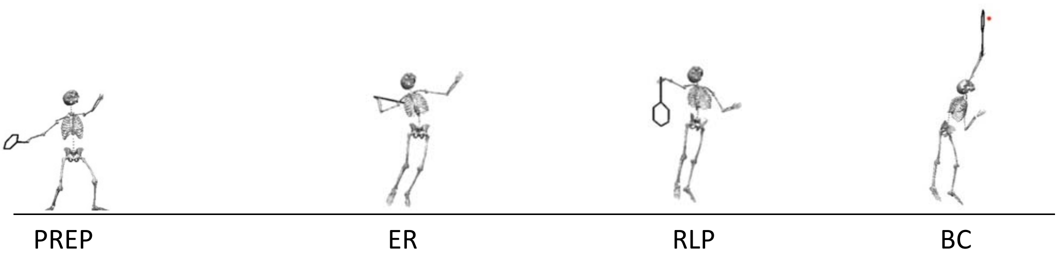


Figure 7.4 – Key instants of the tennis serve the Prep, ER, RLP, and BC.

Joint centres were calculated from a pair of markers placed across each joint, positioned such that their mid-point coincided with the corresponding joint centre (Worthington et al., 2011). The hip joint centres were calculated using the ‘hip joint centring algorithm’ (Davis et al., 1991) from markers placed over the left and right anterior superior iliac spine and the left and right posterior super iliac spine. Lower and upper back motions were defined using the four markers on the pelvis in addition to markers placed over the proximal (sternal) and distal (clavicular) ends of the sternum as well as the spinous process of L1, T10, and C7 (Roosen, 2007).

Local reference frames were defined comprising a three–dimensional full body 18 segment representation of a player. These segments were head and neck; upper back; lower back; pelvis 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two segment foot. A local coordinate system was defined for each segment using three markers on the segment itself. This allowed segment orientations and joint angles to be calculated. The origin of each reference frame was located at the lower joint centre of the segment when the participant stood in the anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the participant’s right (flexion-extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with the y-axis pointing forwards, the x-axis pointing to the right and the z-axis representing the upwards vertical.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) in order to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using a xyz sequence representing an initial rotation about the x-axis of the parent, followed by the rotation about a floating y-axis of the parents and finally the z-axis of the child. These rotations corresponded to the flexion-extension, abduction-adduction, and longitudinal rotation, respectively (Worthington, 2013).

7.2.4 Calculation of Ball Velocity

Curves were fit separately to the pre- and post-impact phases of the tennis ball in each of the three directions in accordance with Equation 1 (McErlain-Naylor et al., 2015).

$$b = \frac{1}{k} \cdot \ln(1 + k \cdot v_{\circ} \cdot t), \tag{1}$$

where b = displacement, t = time, k and v_0 are constants.

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilising a Trust-Region algorithm to determine values for k and v_0. Time of impact was determined as the mean time at which the pre- and post-impact curves crossed in each plane, with differentiation of the three post-impact curves enabling the determination of the resultant instantaneous velocity at this time (McErlain-Naylor et al., 2015).

7.2.5 Statistical Analysis

Twenty-nine parameters were calculated for each trial, describing elements of tennis serve technique that have previously been linked to speed in literature or thought to be linked to speed. All statistical analysis was performed within Statistical Package for Social Sciences v 22 (IBM Corporation, US). The variation observed in each technique parameters were assessed using stepwise linear regression. Due to the recommended suggestion to use only one variable per five subjects, a maximum of three variables were included in the predictive equation with the requirement for inclusion of a variable being $P < 0.10$.

7.3 Results

Speed Comparisons

The results show that players had a similar average no matter which direction they were hitting the ball to (Table 7.1).

Table 7.1 – The min, max, average and standard deviation of speed in the four directions of all participants.

Direction	**min**	**max**	**mean ±SD**
Left Centre Court Line	99	126	114 ± 7
Advantage Court	85	129	111 ± 13
Right Centre Court Line	105	127	116 ± 7
Deuce Court	89	118	107 ± 8

Left Centre Court Line

The seventeen tennis players participating in this study had ball speeds of 99 mph – 126 mph (114 mph ± 7 mph) when serving to the left centre court line (Table 7.2). There was no variable that was significant in predicting speed when hitting in the direction of the left centre court line.

Table 7.2 – Details of the min, max, mean and SD of each technique calculated for left centre court line.

technique parameter	min	max	mean ± SD
ball speed	99 mph	126 mph	114±7 mph
knee extension; prep	86°	140°	112±3°
trunk rotation; ER	3°	29°	18±7°
trunk rotation; RLP	-20°	19°	8±10°
trunk rotation; BC	-11°	11°	.41±5°
trunk extension; ER – BC	206°	240°	220±9°
trunk flexion; ER – BC	175°	199°	187±8°
trunk lateral flexion; max, ER – BC	-15°	33°	9±13°
trunk lateral flexion; max, RLP – BC	-24°	24°	-.79±14°
shoulder ext rotation max, ER – BC	38°	99°	62±16°
shoulder internal rotation; RLP – BC	-101°	46°	68±16°
shoulder internal rotation; ER – BC	-79°	-2°	-38±21°
shoulder abduction; ER – BC	9°	85°	41±19°
shoulder abduction; RLP – BC	-82°	66°	19±39°
elbow extension angle; ER	43°	84°	64± 10°
elbow extension angle; RLP	42°	95°	69 ± 14°
elbow extension angle; BC	169°	190°	176 ± 5°
elbow pronation; ER	-107°	-39°	-76 ± 18°
elbow pronation; RLP	-105°	-58°	-78 ± 13°
elbow pronation; BC	-81°	-23°	-62 ± 14°
elbow pronation; ER – BC	-7°	41°	17 ± 13°
elbow pronation; max, ER - BC	-79°	-24°	-59 ± 15°
elbow pronation; min, ER - BC	-107°	-64°	84 ± 12°
wrist extension; ER	170°	285°	218 ± 33°
wrist extension; RLP	197°	295°	233 ± 31°
wrist extension; BC	176°	254°	203 ± 30°
timing; Prep to BC	0.19 s	0.48 s	0.31 ± 0.07 s
timing; Prep to ER	0.03 s	0.31 s	0.14 ± 0.08 s
timing; RLP to BC	0.09 s	0.12 s	0.11 ± 0.01 s
timing; ER to BC	0.13 s	0.19 s	0.16 ± 0.02 s

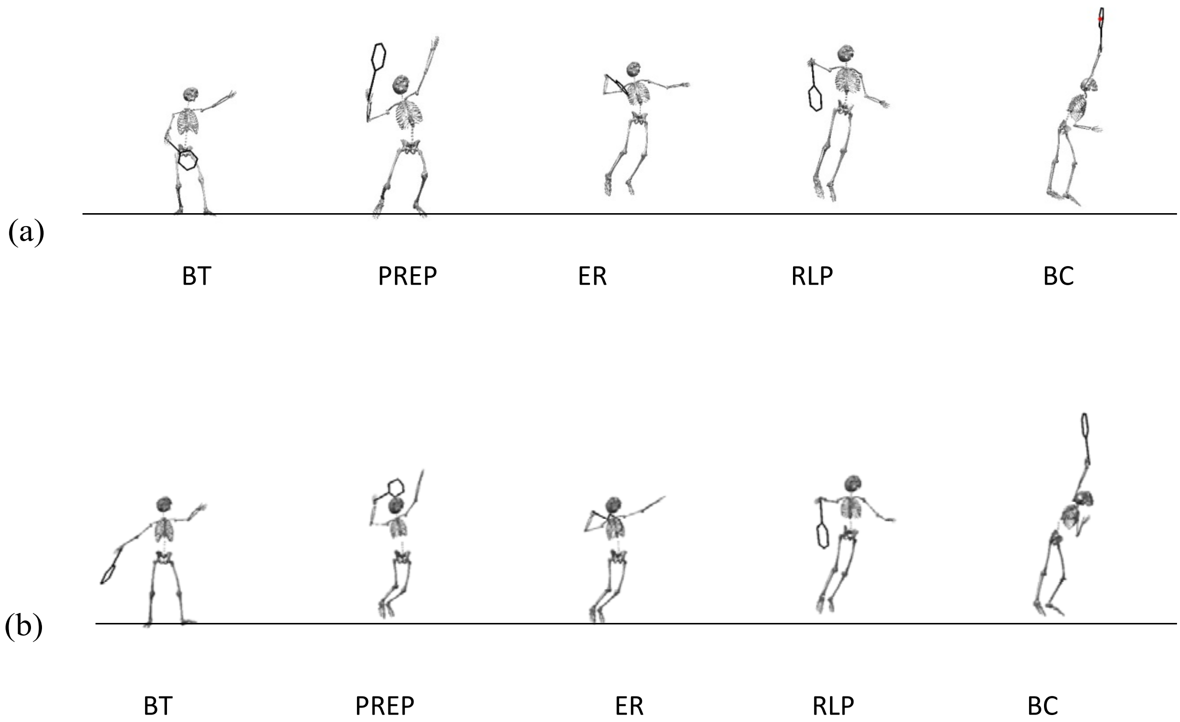


Figure 7.5 – Comparison of (a) fastest and (b) slowest participants' (a left-handed player) technique at key instants for left centre court line.

Visual inspection of the technique differences between the fastest and slowest participants shows that the faster participant has a larger degree of knee flexion at the preparation key instant. It is at ER point in the serve that the faster participant begins to leave the ground. At the point of ball contact the faster participant has more of a straight line from the racket, wrist, and elbow than that of the slower participant.

Advantage Court

The seventeen tennis players participating in this study had speeds of 85 mph – 129 mph (111 mph ± 13 mph) when serving towards the advantage court (Table 7.3).

Table 7.3 – Details of the min, max, mean, and SD of each technique parameter calculated for the advantage court.

technique parameter	min	max	mean ± SD
ball speed	85 mph	129 mph	113 ± 13 mph
knee extension; prep	88°	127°	110 ± 11°
trunk rotation; ER	11°	29°	20 ± 5°
trunk rotation; RLP	-19°	17°	8 ±10°
trunk rotation; BC	-8°	7°	.50 ± 5°
trunk extension; ER – BC	208°	240°	221 ± 8°
trunk flexion; ER – BC	174°	201°	188 ± 8°
trunk lateral flexion; max, ER –BC	-12°	25°	9 ± 12°
trunk lateral flexion; max, RLP – BC	-22°	24°	-.19 ± 13°
shoulder ext rotation max, ER –BC	38°	89°	65 ± 16°
shoulder internal rotation; RLP – BC	-.72°	-.4°	.34 ± 19°
shoulder internal rotation; ER –BC	-.101°	-.43°	-.66 ± 15°
shoulder abduction; ER – BC	11°	83°	43 ± 19°
shoulder abduction; RLP –BC	-.65°	63°	22 ± 34°
elbow extension angle; ER	43°	84°	66 ± 10°
elbow extension angle; RLP	41°	99°	70 ± 14°
elbow extension angle; BC	168°	190°	177 ± 6°
elbow pronation; ER	-.104°	-.37°	-.76 ± 17°
elbow pronation; RLP	-.101°	-.58°	-77 ± 13°
elbow pronation; BC	-83°	-26°	-65 ± 15°
elbow pronation; ER – BC	-17°	39°	12 ± 17°
elbow pronation; max, ER – BC	-76°	-26°	-59 ± 14°
elbow pronation; min, ER – BC	-105°	-63°	-88 ± 13°
wrist extension; ER	163°	280°	221 ± 33°
wrist extension; RLP	194°	296°	235 ± 32°
wrist extension; BC	175°	252°	203 ± 30°
timing; Prep to BC	0.21 s	0.50 s	0.32 ± 0.08 s
timing; Prep to ER	0.06 s	0.30 s	0.14 ± 0.08 s
timing; RLP to BC	0.04 s	0.15 s	0.11 ± 0.02 s
timing; ER to BC	0.13 s	0.22 s	0.18 ± 0.02 s

Table 7.4 – Linear regression results for advantage court.

model	technique	coefficient	p-value	percent explained
1	Trunk rotation RLP	-1.802	.047	23.8%

The best individual predictor of speed after impact in the advantage court was trunk rotation angle from RLP - BC phase explaining 23.8% (Figure 7.7) of the variation in speed (Table 7.4). The regression showed that players with the fastest time tended to have a larger trunk rotation angle.

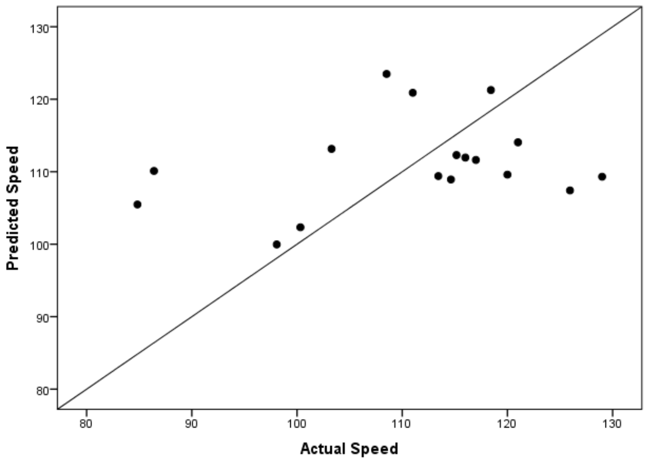


Figure 7.6 – Predicted and actual tennis serve speeds for the regression equation for the advantage court.

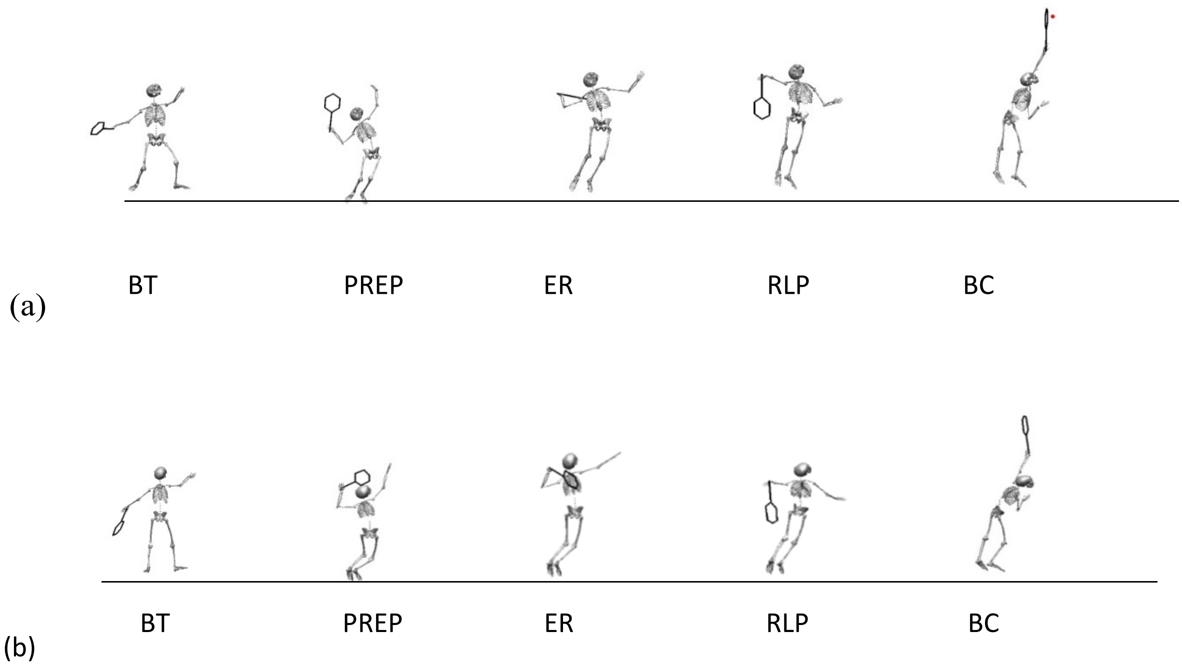


Figure 7.7 – Comparison of the (a) fastest and (b) slowest participants' (a left handed player) technique at key instants for the advantage court.

Visual inspection of the data shows that at the preparation key instant the faster player leans his trunk backwards more than the slower participant. At the ER key instant there is a slight difference in wrist angle between the two participants. The faster player tended to have a straighter wrist than the slower participant Figure 7.7).

Right Centre Court Line

The seventeen tennis players participating in this study had ball speeds of 105 mph – 127 mph (116 mph ± 7 mph) when serving towards the right centre court line (Table 7.5).

Table 7.5 – Details of the min, max, mean, and SD of each technique parameter calculated for right centre court line.

technique parameter	min	max	mean ± SD
ball speed	105 mph	127 mph	116 ± 7 mph
knee extension; prep	87°	126°	109 ± 11°
trunk rotation; ER	4°	28°	18 ± 6°
trunk rotation; RLP	0°	20°	12 ± 10°
trunk rotation; BC	-12°	6°	.48 ± 5°
trunk extension; ER – BC	208°	239°	220 ± 8°
trunk flexion; ER – BC	174°	202°	187 ± 7°
trunk lateral flexion; max, ER – BC	-15°	36°	11 ± 13°
trunk lateral flexion; max, RLP – BC	-24°	23°	-.49 ± 15°
shoulder ext rotation max, ER – BC	42°	100°	61 ± 16°
shoulder internal rotation; RLP – BC	-.80°	0°	-35 ± 21°
shoulder internal rotation; ER – BC	-.94°	-.41°	-70 ± 14°
shoulder abduction; ER – BC	11°	86°	41 ± 22°
shoulder abduction; RLP – BC	-94°	-63°	19 ± 42°
elbow extension angle; ER	43°	88°	65 ± 11°
elbow extension angle; RLP	43°	100°	70 ± 14°
elbow extension angle; BC	169°	191°	176 ± 6°
elbow pronation; ER	-105°	40°	-77 ± 16°
elbow pronation; RLP	-98°	-.56°	-80 ± 13°
elbow pronation; BC	-81°	-40°	-64 ± 13°
elbow pronation; ER – BC	-3°	58°	16 ± 15°
elbow pronation; max, ER – BC	-77°	-40°	-61 ± 13°
elbow pronation; min, ER – BC	-105°	-67°	-87 ± 10°
wrist extension; ER	153°	280°	211 ± 35°
wrist extension; RLP	145°	295°	225 ± 37°
wrist extension; BC	172°	253°	199 ± 30°
timing; Prep to BC	0.20 s	0.42 s	0.31 ± 0.06 s
timing; Prep to ER	0.04 s	0.24 s	0.13 ± 0.06 s
timing; RLP to BC	0.10 s	0.14 s	0.11 ± 0.01 s
timing; ER to BC	0.15 s	0.21 s	0.18 ± 0.02 s

(a)

(b)

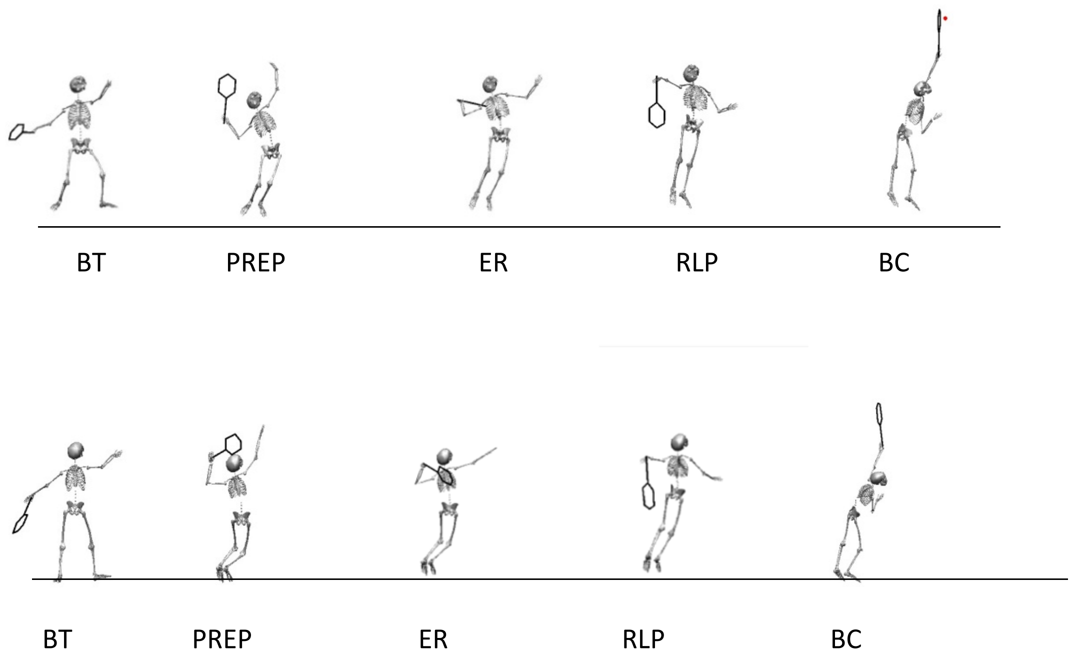


Figure 7.8 – Comparison of (a) fastest and (b) slowest participants' technique at key instants for right centre line.

Visual inspection of the data shows that in the preparation key instant the faster player has a larger degree of knee flexion on his dominate leg. He also has a wider stance than that of the slower participant. At the racket lowest point position both players are leaning their trunk towards the ball in preparation of hitting it (Figure 7.8).

Deuce Court

The seventeen tennis players participating in this study had ball speeds of 89 mph – 118 mph (106 mph ± 8 mph) when serving towards the deuce court. Details of the range, mean, and standard deviation of each calculated technique parameter for the group of participants are provided in Table 7.6.

Table 7.6 – Details of the min, max, mean, and SD of each technique parameter calculated for the deuce court.

technique parameter	min	max	mean ± SD
ball speed	89 mph	118 mph	106 ± 8 mph
knee extension; prep	92°	135°	111 ± 11°
trunk rotation; ER	3°	28°	18 ± 6°
trunk rotation; RLP	-1°	20°	12 ± 5°
trunk rotation; BC	-19°	8°	-2.3 ± 6°
trunk extension; ER – BC	207°	242°	220 ± 9°
trunk flexion; ER – BC	176°	215°	188 ± 10°
trunk lateral flexion; max, ER – BC	-10°	35°	11 ± 12°
trunk lateral flexion; max, RLP – BC	-21°	23°	-.32 ± 13°
shoulder ext rotation max, ER – BC	40°	95°	69 ± 16°
shoulder internal rotation; RLP –BC	-67°	-4°	-29 ± 20°
shoulder internal rotation; ER – BC	-93°	-38°	63 ± 15°
shoulder abduction; ER – BC	8°	84°	40 ± 21°
shoulder abduction; RLP – BC	-93°	62°	18 ± 40°
elbow extension angle; ER	44°	77°	63 ± 10°
elbow extension angle; RLP	40°	99°	67 ± 13°
elbow extension angle; BC	165°	186°	175 ± 6°
elbow pronation; ER	-101°	-43°	-76 ± 16°
elbow pronation; RLP	-94°	-52°	-75 ± 14°
elbow pronation; BC	-78°	-31°	-61 ± 12°
elbow pronation; ER – BC	-17°	44°	14 ± 20°
elbow pronation; max, ER – BC	-77°	-33°	-59 ± 14°
elbow pronation; min, ER – BC	-102°	-65°	-83 ± 12°
wrist extension; ER	158°	286°	217 ± 33°
wrist extension; RLP	189°	294°	231 ± 31°
wrist extension; BC	175°	255°	203 ± 29°
timing; Prep to BC	0.20 s	0.48 s	0.32 ± 0.07 s
timing; Prep to ER	0.02 s	0.30 s	0.14 ± 0.08 s
timing; RLP to BC	0.10 s	0.13 s	0.11 ± 0.01 s
timing; ER to BC	0.15 s	0.21 s	0.18 ± 0.02 s

Table 7.7 – Stepwise linear regressions results for deuce court.

model	technique	coefficient	p-value	percent explained
1	Timing; ER---BC	---259.251	.015	33.6%

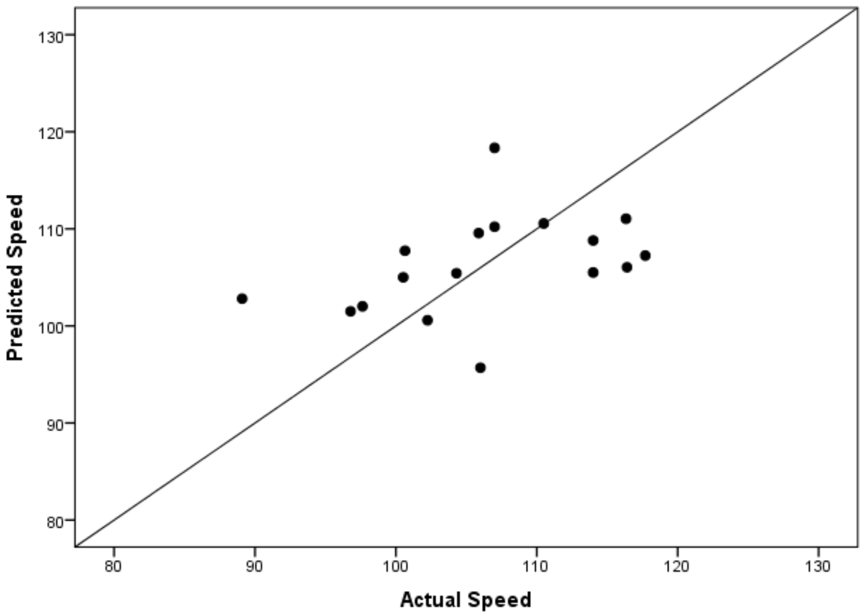


Figure 7.9 – Comparisons of predicted and actual tennis serve speeds for the regression equation at 33.3%.

The best individual predictor velocity after impact was timing; ER-BC phase explaining 33.63%. The results showed that the participants with the fastest serve speeds took the least amount of time to move between the phase (Table 7.7, Figure 7.9).

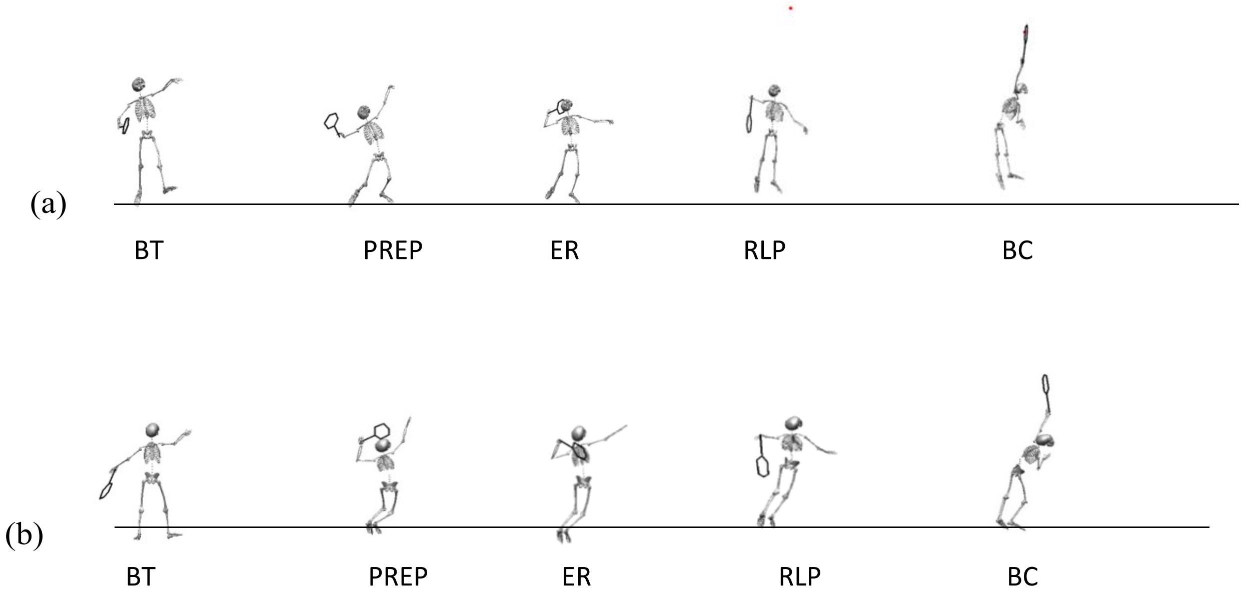


Figure 7.10 – Comparison of the (a) fastest and (b) slowest participants' technique (a left-handed player) at the key instants for the deuce court.

Visual inspection of the data shows that at the prep phase the faster participant has more knee flexion that that of the slower player. The slower participant continues to have a slight knee bend at the ER key instant, while at this point the faster participant is already beginning to straighten his body (Figure 7.10).

7.4 Discussion

While previous studies have reported correlations between ball speed after impact and a variety of different elements of the tennis serve technique (Elliott, 1995: Reid et al., 2007: Gordon and Dapena, 2006), studies comparing kinematics of serves to different locations in the service box are limited (Chow, 2009). Previous studies have focused on the importance of the shoulder, elbow, and wrist to the service action (Elliott, 1995: Reid et al, 2007: Gordon and Dapena, 2006). This study used stepwise linear regression in order to account for interactions between technique parameters with the aim of identifying the key variables that determine ball speed after impact within the four directions of the tennis court. The results of this investigation suggest the main variations in ball speed after impact among tennis players occur when players hit the ball towards the deuce, advantage, or right centre line of the court.

For left and right centre court lines the regression showed that there were no variables that had a significant impact on speed. This could be because when hitting down the centre court line the participants are not doing anything differently within their techniques in order to achieve the desired outcome.

When hitting towards the advantage court the best predictor of speed was trunk rotation angle between the RLP-SC phases, explaining 23.8% of post impact speed. This result supports the one found by Fleisig et al., (2003) that found that the trunk plays an important role in the tennis serve speed. One of the most prominent principles in sports movement is the proximal-to-distal sequencing that suggests that maximize the speed at the distal end of a linked system. The trunk helps coordinate the action between the upper and lower limbs and it doing so assists in the increasing range of racket movement during the lop of the racket behind the player's back (Elliot, 1993). While the legs provide the initial drive it is the trunk that provides the rotary actions that the body needs in order to complete the tennis service action. The trunk movement provides the forward acceleration needed to complete the tennis serve.

When hitting towards the deuce court the strongest indicator of speed was timing; ER-SC, explaining 33.6% of post impact speed. The fastest tennis players took a shorter amount of time moving through this phase. A One-way ANOVA showed that the only significant difference for the parameters across the four directions was speed for the right centre court line and deuce courts.

Visual inspection of the service technique between the fast and slow players also showed some key differences. One difference was no matter which direction all the faster players had a larger degree of knee flexion at the preparation key instant than that of the slower player. This can be because the leg bend starts the service action. Players transfer energy up the body from the lower limbs to the upper limbs in order to have the power they need for a quick serve. Faster players also could be seen with more trunk rotation in their service action. By having more trunk rotation this provides players with the mechanism

to apply a whip like motion needed for a quick serve.
Small sample sizes are a common problem when studying the populations in the current study. The data set of seventeen tennis players limited the number of technique parameters that could be confidently identified as explaining the variation in speed to three.

The results of this study represent relationships between tennis serve technique and speed among a group of eighteen tennis players, they indicating the key aspects of the tennis serve technique that differentiated velocities within the group. Future studies should address the effect of changing aspects of technique on an individual. This would enable the effect of technique alteration to be addressed.

7.5 Conclusion

This study has identified that when hitting the serve down the left centre service line that there was no significant difference in technique for the participants. When hitting in the direction of the right centre court line and the advantage court shoulder abduction angle; RLP-ER was the best predictor of post impact speed at 35.2% and 23.8% respectively. Respectively when hitting towards the deuce court timing from the ER-BC phase accounted for 29.3% of the variation in tennis serve speed; with the fastest players showing a quicker time for this phase of the tennis serve.

Although further work is needed to fully understand why some players can serve the ball faster than others this investigation provides a basis for further study. The key parameters identified.

CHAPTER 8: VARIABILITY IN THE TENNIS SERVE

8.1 Introduction

Tennis is a game enjoyed by players of all standards and ages. While it is important to master a number of strokes, the serve is arguably the most important facet of the game (Elliott, 1988). Tennis players are continually being challenged to increase their serve velocity in an attempt to dominate their opponent (Fleisig et al., 2003). Variability can occur in not only motor performance but also in tactical situations and environmental conditions that may affect performance (Mendes et al., 2011). Due to a high requirement of athletes' physical exertion, such as speed, power, precision, flexibility and coordination, the skill is always a challenge for players to accomplish with a high quality (Li et al., 2016). In order to be successful at tennis a player must be able to hit the serve accurately and consistently during their match. The speed of a tennis serve was an important criterion of the serve performance. An increasing serve speed reduces the time for the opponents to prepare to return the ball successfully and increases the chances of the server winning the point (Vaverka and Cernosek, 2016).

Despite a long history of research describing movement variability and its functional relevance to human movement (Hatze, 1986; Winter, 1984) variability in sporting motions was often considered noise (Bartlett et al., 2007). Although there has been research into variability and the tennis serve, overall research into this area has been limited. One study by Antunez et al. (2012) found that consistency in speed and location of the tennis serving hand around impact is positively related to serve speed and accuracy. A 2014 study by Hernandez-Davo et al., showed that variability improved both velocity and accuracy.

In tennis, the two critical things that can affect the outcome of a game are speed and the percentage of serves being in. Currently there is no consensus regarding variability and how it affects the tennis service action or speed after impact. The aim of the current study was therefore to identify how consistent a tennis player was in their service technique when hitting in four different directions and the effects on speed and percentage in.

8.2 Methodology

8.2.1 Participants

Seventeen male players (mean ± standard deviation: age 19.7 ± 2.3 years; height 1.82 ± 0.05 m; body mass 75.3 ± 7.3 kg) participated in this investigation. Each player performed forty tennis serves which were recorded using 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK), operating at 400 Hz. The camera set-up was positioned to include the half of the court that the participant was performing in, approximately 7 x 6 x 3 m. All players were at least county standard. No participants were aware of any injury/illness that would have affected their performance within the testing protocol. The testing procedures were explained to each participant in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All participants conducted a thorough warm-up prior to the start of the data collection.

8.2.2 Data Collection

Forty-four 14 mm retro-reflective markers were attached to each participant (Figure 8.1), positioned over bony landmarks. The players used their own racket for the data collection. Each racket was fitted with seven strips of reflective tape, plus a marker on the base of the racket (Figure 8.2) and new Wilson tennis balls were used with six strips of reflective tape attached to the ball (Figure 8.2). Static and range of motion (ROM) trials were performed for each participant (Figure 8.2), allowing body segment lengths and a neutral spine position to be calculated (Ranson et al., 2008). Anthropometric measurements were taken in accordance with the geometric model of Yeadon (1990) enabling participant - specific segmental inertia parameters to be determined for each player.

Figure 8.1 – The marker positions used in the tennis study.

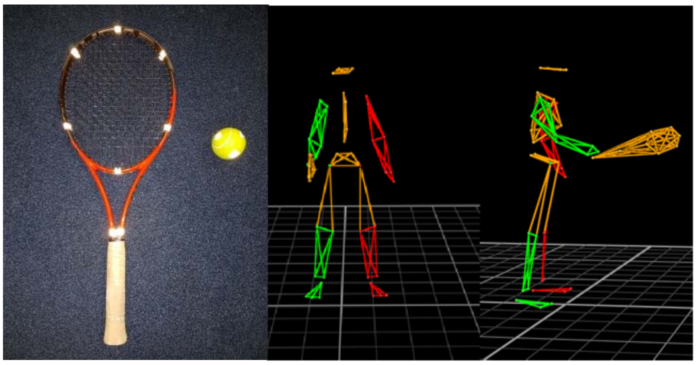


Figure 8.2 - The marker positions used in the tennis study; static position of participant used in the tennis study.

8.2.3 Data Processing

The best trial with maximum speed and minimal marker loss, in each of the four directions of the tennis service court (deuce court, advantage court, right centre, and left centre) was identified for each participant. These trials were manually labelled and processed using the Vicon Workstation and BodyBuilder software (OMG Plc, Oxford, UK). For each trial four key instants were identified (Figure 8.4); the preparation (prep); end of retraction (ER); racket lowest point (RLP); and ball contact (BC) (Figure 8.4). The instant of preparation was identified as when the knee angle was most flexed prior to jumping. The instant of ER was identified by the horizontal position of the racket behind the participant prior to the forward swing. The instant of RLP was identified as the minimal vertical position of the racket prior to the forward swing of the racket. The instant of BC was identified as the frame where the ball and racket were closets. Kinematic data were filtered using a fourth order Butterworth filter (double – pass) with a low pass cut off frequency of 30 Hz.

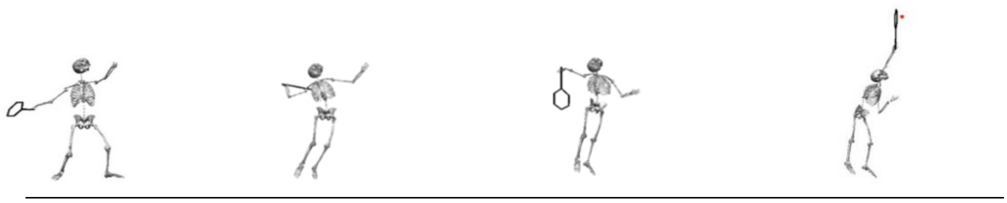


Figure 8.4 – The position for the Prep, ER, RLP, and BC for key instants of the tennis serve.

Joint centres were calculated from a pair of markers placed across each joint, positioned such that their mid-point coincided with the corresponding joint centre (Worthington et al., 2011). The hip joint centres were calculated using the 'hip joint centre algorithm' (Davis et al., 1991) from markers placed over the left and right anterior superior iliac spine and the left and right posterior super iliac spine. Lower and upper back motions were defined using the four markers on the pelvis in addition to markers placed over the proximal (sternal) and distal (clavicular) ends of the sternum as well as the spinous process of L1, T10, and C7 (Roosen, 2007).

Local reference frames were defined comprising a three–dimensional full body 18 segment representation of a player. These segments were head and neck; upper back; lower back; pelvis 2 x humerus; 2 x radius; 2 x hand; 2 x femur; 2 x tibia; and 2 x two segment foot. A local coordinate system was defined for each segment using three markers on the segment itself. This allowed segment orientations and joint angles to be calculated. The origin of each reference frame was located at the lower joint centre of the segment when the participant stood in the anatomical position. The z-axis pointed upwards along the longitudinal axis of the segment, the x-axis pointed towards the participant's right (flexion - extension axis of the joint) and the y-axis pointed forwards. Similarly, a global coordinate system was defined with the y-axis pointing forwards, the x-axis pointing to the right and the z-axis representing the upwards vertical.

Joint angles were calculated using Cardan angles, defining the rotation applied to the parent coordinate system (proximal segment) in order to bring it into coincidence with the coordinate system of the child segment (distal segment). Rotation angles were calculated using a xyz sequence representing an initial rotation about the x- axis of the parent, followed by the rotation about a floating y-axis of the parents and finally the z-axis of the child. These rotations corresponded to the flexion - extension, abduction - adduction, and longitudinal rotation, respectively (Worthington et al., 2013).

8.2.2 Calculation of Ball Velocity

Curves were fitted separately to the pre - and post - impact phases of the tennis ball in each of the three directions in accordance with Equation 1 (McErlain-Naylor et al., 2015).

$$b = \frac{1}{k} \cdot \ln(1 + k \cdot v_{\circ} \cdot t), \qquad (1)$$

where b = displacement, *t* = time, *k* and v_0 are constants.

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilising a Trust-Region algorithm to determine values for k and v_0. Time of impact was determined as the mean time at which the pre- and post-impact curves crossed in each plane, with differentiation of the three post-impact curves enabling the determination of the resultant instantaneous velocity at this time (McErlain-Naylor et al., 2015).

8.2.4 Data Reduction

Initially mean and standard deviation values were calculated for speed in four directions for each of the participants. Also, the percentage of tennis serves that were successfully hit in was calculated.

Out of seventeen participants, three was chosen to be analysed in more detail. It was chosen to study the variability of the participants while hitting in towards the left centre court line. The variability of the ball speed of participant 15 was considerably higher than the rest of the group (Table 8.1), therefore he was chosen as the least consistent player. The speed of participant 9 had a lower variability than other participants and he was chosen as the most consistent player in the study, while participant 10 had an average variability of speed and therefore chosen as the average player. For the three participants', knee, elbow, wrist, and shoulder data were compared. A simple visual inspection was carried out for the participants. While this clearly lacks the scientific rigour of a statistical test, it was thought to be suitable in this case given the more investigative and descriptive nature of this initial variability study.

8.3 Results

Left Centre Court Line

When hitting in the direction of the left centre court line the participants had a speed range of 91 – 164 mph (128 ± 52 mph). The results also showed that the participants hit the tennis serve in between 25 - 80% (38% ± 52%) of the time (Table 8.1).

Table 8.1 – The percentage of tennis serve in, min, max, and standard deviation of speed for left centre court line.

participant	percent In	min (mph)	max (mph)	std (mph)
P1	50%	110	122	117 ± 3
P2	44%	94	111	104 ± 6
P3	56%	96	126	114 ± 8
P4	38%	109	126	117± 5
P5	38%	95	109	105 ± 3
P6	67%	95	109	102 ± 4
P7	56%	106	115	111 ± 3
P8	75%	95	108	101 ± 4
P9	57%	94	104	97 ± 3
P10	80%	91	113	101 ± 5
P11	25%	108	119	115 ± 3
P12	63%	92	117	106 ± 7
P13	38%	98	106	102 ± 2
P14	38%	93	109	104 ± 4
P15	59%	104	118	112 ± 4
P16	44%	100	119	110 ± 6
P17	63%	102	118	111 ± 5

Advantage Court

When hitting in the direction of the advantage court the participants had a speed range of 81 - 129 mph (105 ± 34mph). The results also show that the participants hit the tennis serve in 38 - 88% (39 ± 61%), (Table 8.2).

Table 8.2 – The percentage of serves in, min, max, and standard tennis deviation of speed for advantage court.

participant	percent In	min (mph)	max (mph)	std (mph)
P1	50%	120	129	125 ± 6
P2	75%	99	113	106 ±10
P3	50%	81	121	112 ± 15
P4	75%	103	118	114 ± 6
P5	38%	96	112	105 ± 7
P6	50%	107	111	109 ± 2
P7	88%	99	121	113 ±10
P8	50%	85	109	101± 9
P9	79%	95	105	100± 4
P10	58%	89	105	99 ± 6
P11	50%	86	117	105 ±10
P12	75%	112	115	114 ±2
P13	38%	92	109	102± 6
P14	63%	107	115	110 ±3
P15	75%	108	117	112± 3
P16	63%	102	116	109± 10
P17	75%	106	126	115 ± 7

Right Centre Court Line

When hitting in the direction of the right centre court line the participants had a speed range of 95 - 127mph (111 ± 27mph). The results also show that the participants hit the tennis serve in 33 - 100% (47 ± 67%), (Table 8.3).

Table 8.3 – The percentage of tennis serve in, min, max, and standard deviation of speed for right centre court line.

participant	percent In	min (mph)	max (mph)	std (mph)
P1	50%	117	126	121 ±2.4
P2	75%	103	119	109 ± 6
P3	75%	104	127	120 ± 7
P4	50%	105	125	116 ± 6
P5	38%	102	117	108 ± 5
P6	33%	102	114	109 ± 4
P7	88%	111	118	115 ± 2
P8	63%	95	110	103± 5
P9	50%	101	109	105 ± 3
P10	33%	103	112	106 ±3
P11	50%	112	124	117 ±4
P12	38%	102	120	112± 7
P13	38%	99	110	106 ±4
P14	50%	107	120	113 ±5
P15	100%	111	123	115 ±4
P16	38%	109	122	116± 5
P17	50%	101	121	112 ±6

Deuce Court

When hitting in the deuce court direction the participants had a speed range of 89 - 118 mph (103 ± 21 mph). The results also showed that the participants had a range of 30 - 100% (47 ± 67%) of hitting the serve in for this direction (Table 8.4).

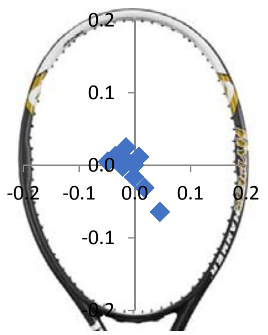
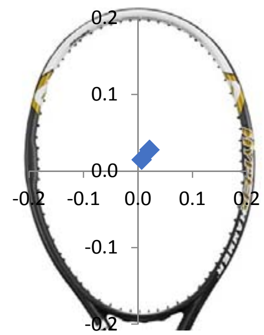
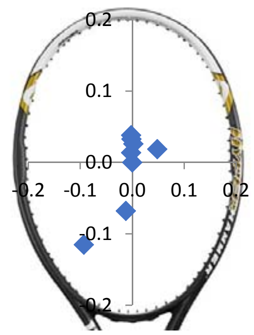
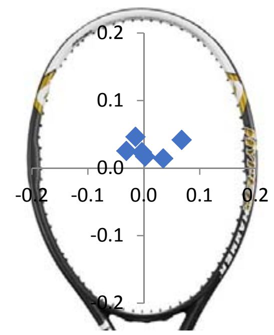
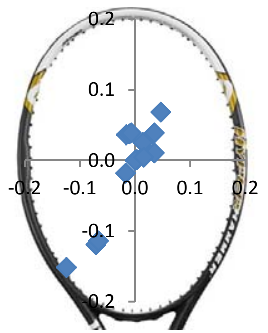
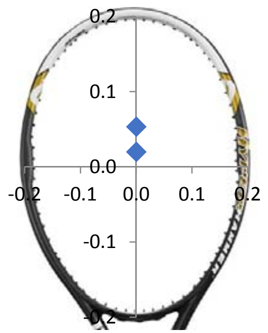
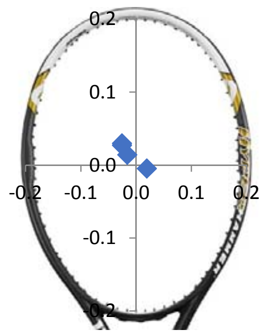
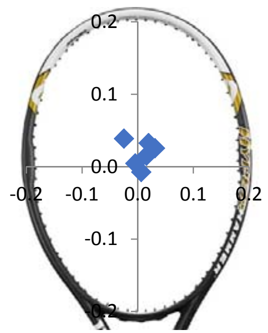
Table 8.4– The percentage of tennis serves in, min, max, and standard deviation of speed for deuce court.

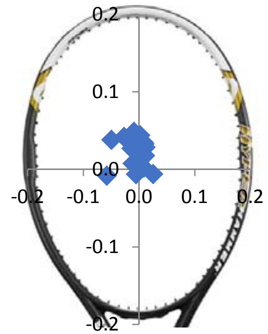
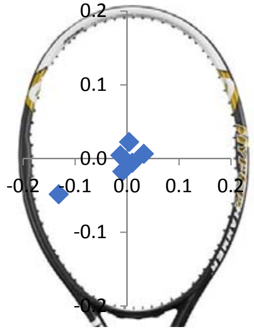
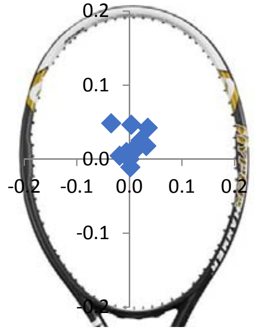
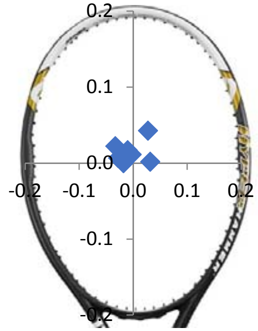
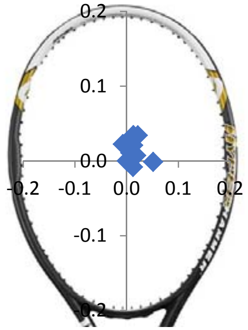
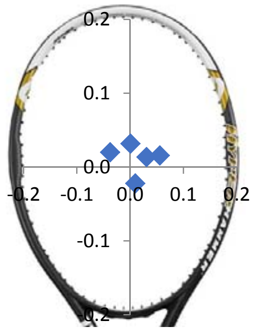
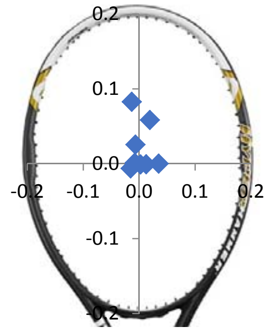
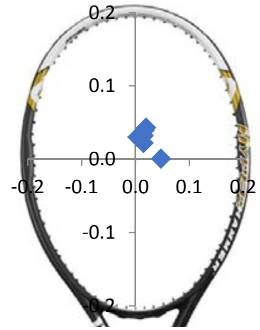
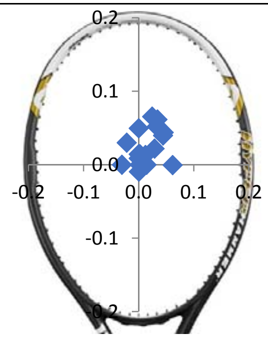
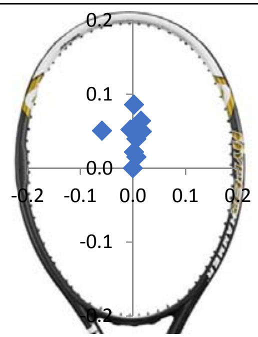
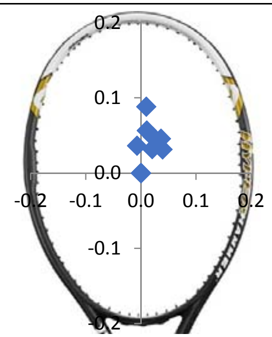
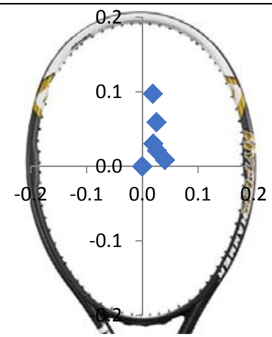
participant	percent In	min (mph)	max (mph)	std (mph)
P1	75%	106	117	111 ±4.9
P2	63%	94	109	102 ± 6
P3	100%	101	117	108 ± 6
P4	69%	101	108	106 ± 3
P5	63%	98	115	107 ± 8
P6	62%	90	110	98 ± 6
P7	75%	102	115	109 ± 5
P8	38%	89	96	93 ±3
P9	30%	90	109	98 ± 7
P10	77%	89	104	98 ±5
P11	13%	100	118	110± 7
P12	75%	101	117	108± 6
P13	63%	96	106	101± 4
P14	75%	94	109	103 ±6
P15	60%	106	114	110± 3
P16	63%	102	116	109 ±10
P17	75%	98	118	108± 7

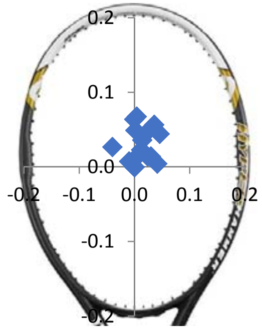
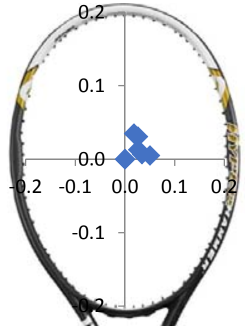
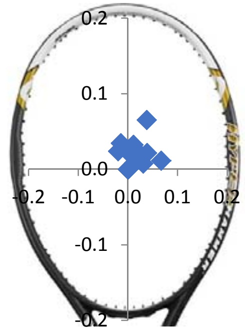
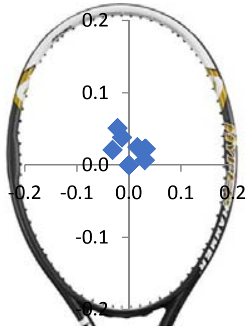
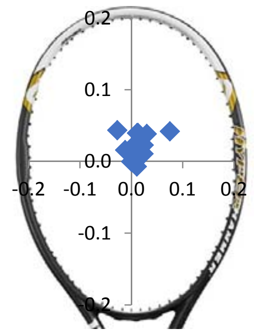
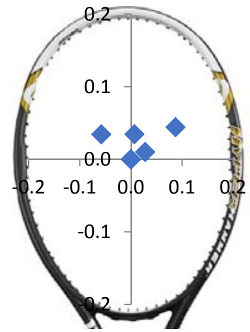
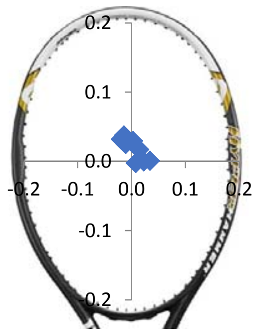
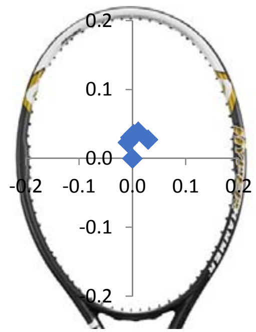
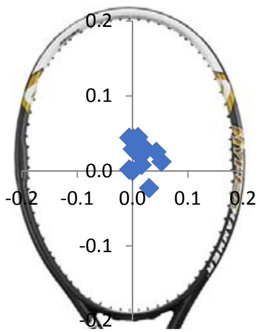
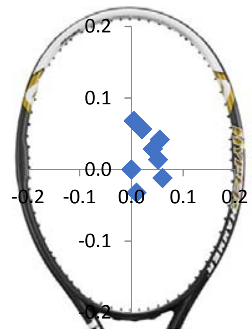
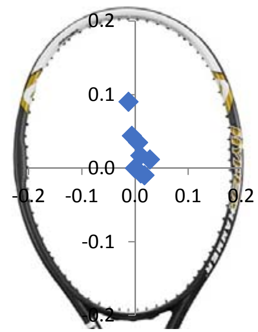
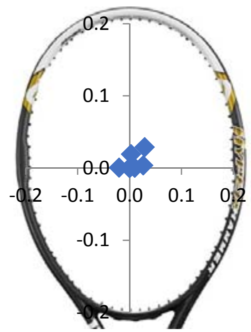
Ball Location on the Racket at Impact

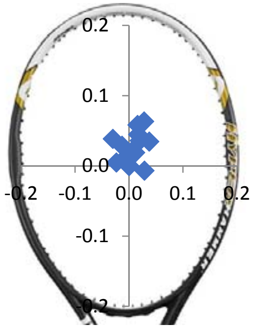
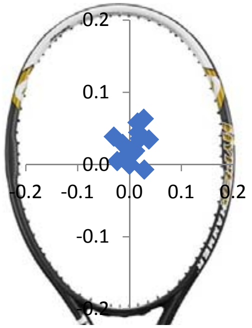
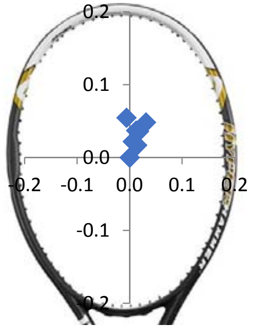
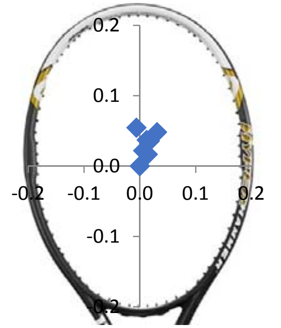
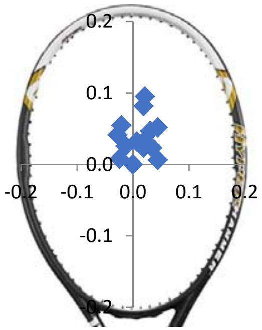
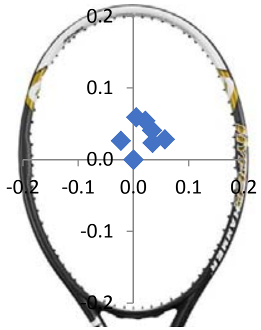
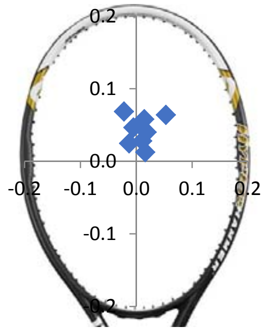
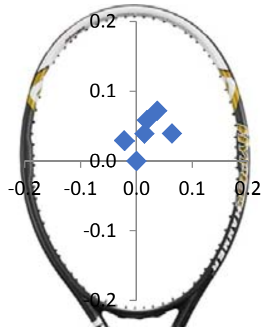
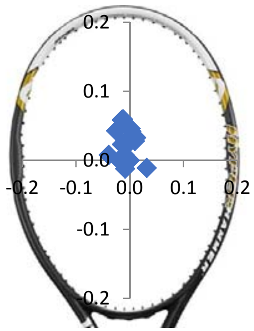
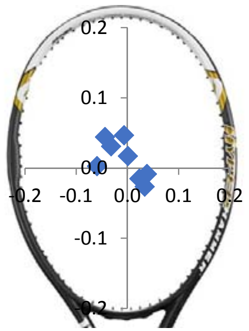
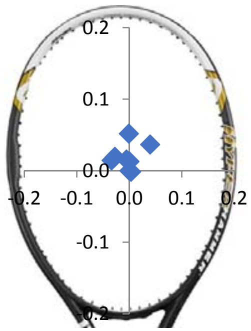
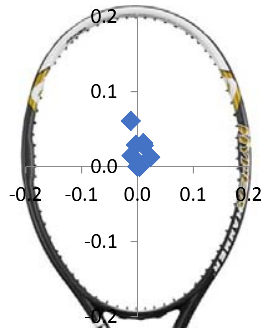
Across the group the data showed that participants tended to hit the ball within a cluster on the racket. The participants hit the tennis ball within the centre of the racket no matter the direction (Table 8.5).

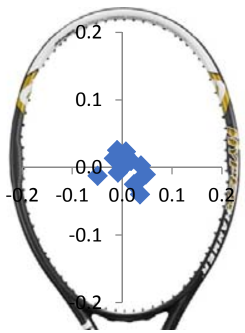
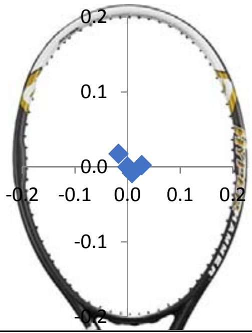
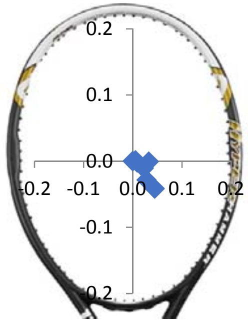
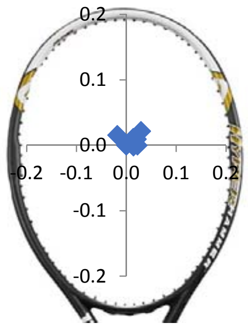
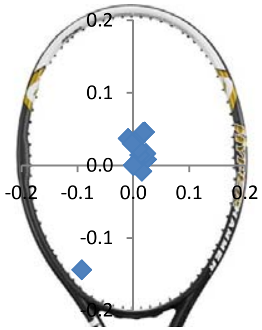
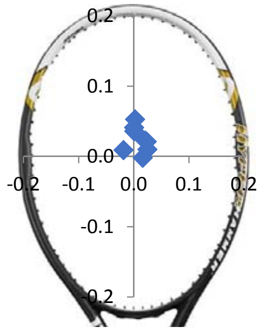
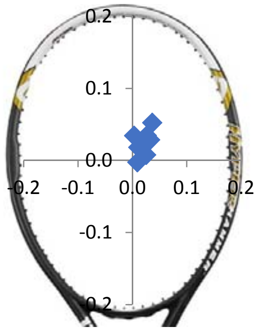
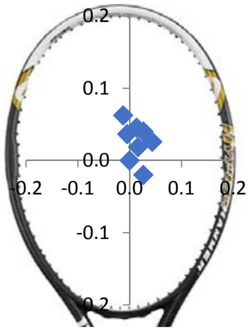
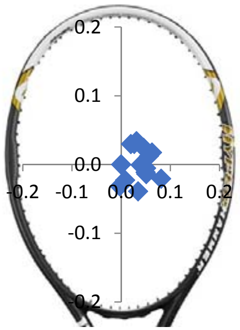
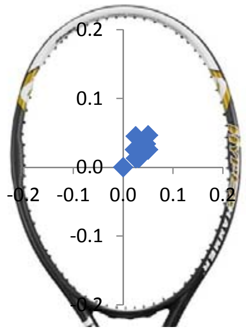
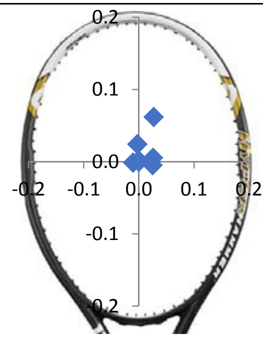
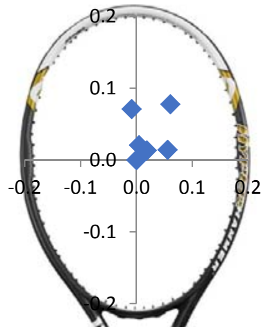
Table 8.5 - Ball location on the racket at impact in each of the four directions at impact.

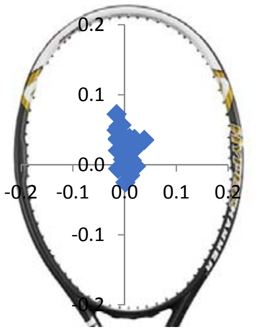
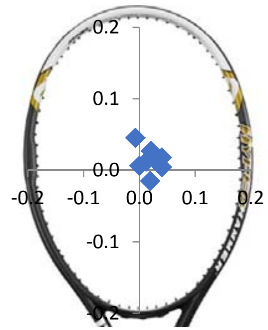
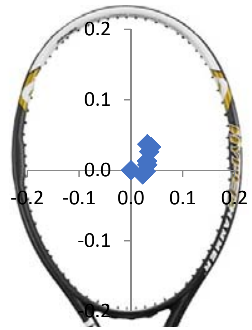
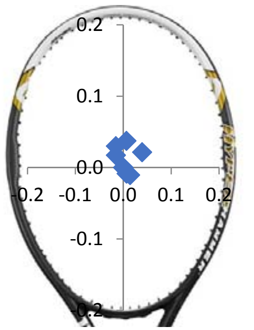
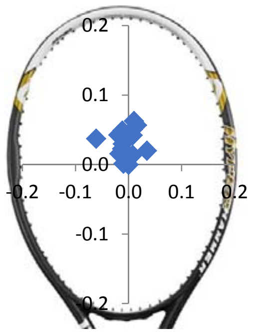
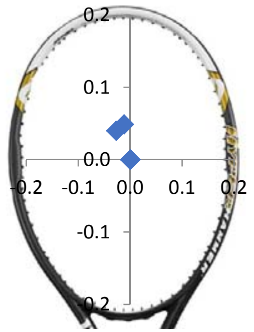
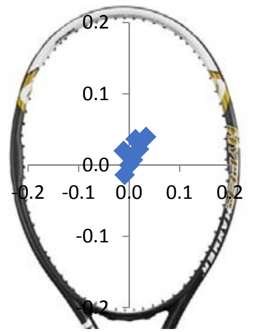
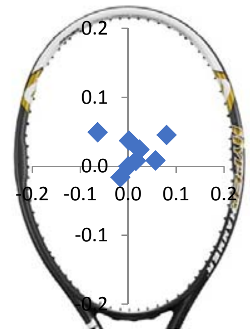
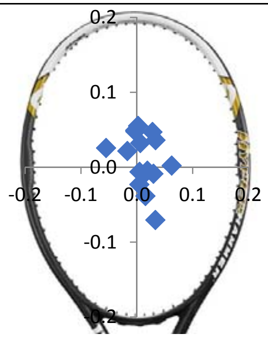
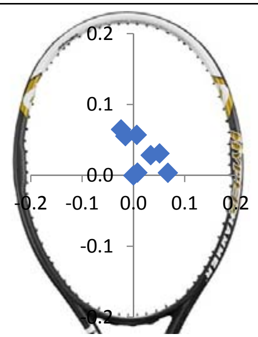
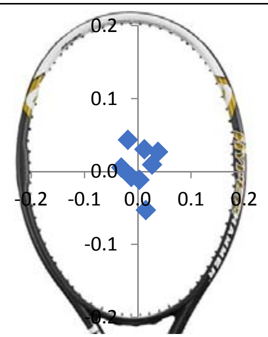
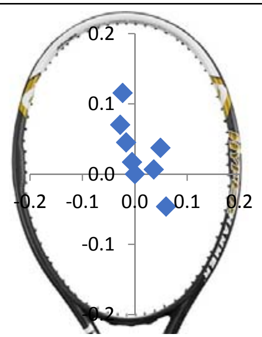
Participant	Left Middle	Left Wide	Right Middle	Right wide
P1				
P2				

P3				
P4				
P5				

P6				
P7				
P8				

P9				
P10				
P11				

P12				
P13				
P14				

P15				
P16				
P17				

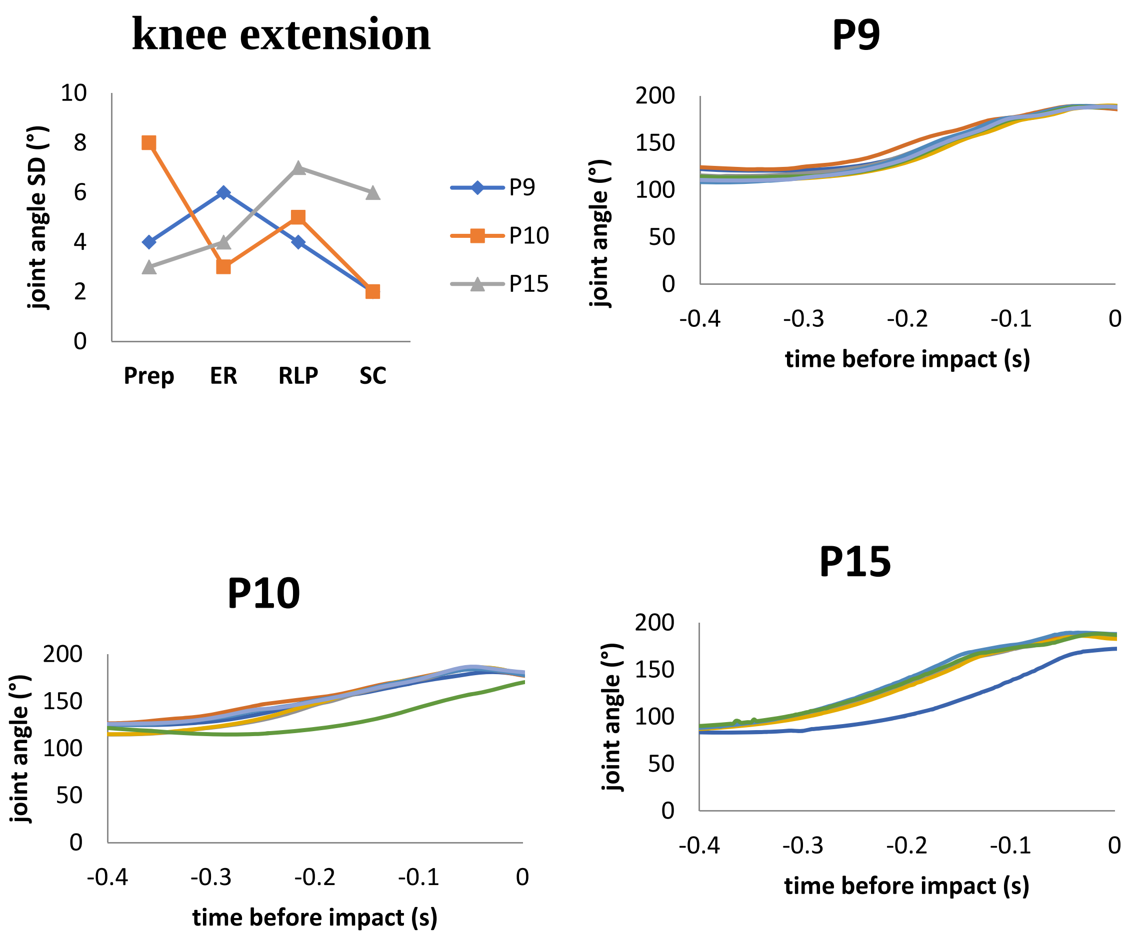


Figure 8.5 – SD of knee extension and flexion through the key instants; knee extension and flexion of all trials plotted.

Examination of the variability data for the knee flexion and extension angle reveals that there was a similar pattern between the three participants (Figure 8.5).There is a lower degree of knee extension at the beginning of the serve and then as the player moves through the service action the knee extension angle becomes larger This reflects that visual data that shows the players have a straight leg at the point of ball contact.

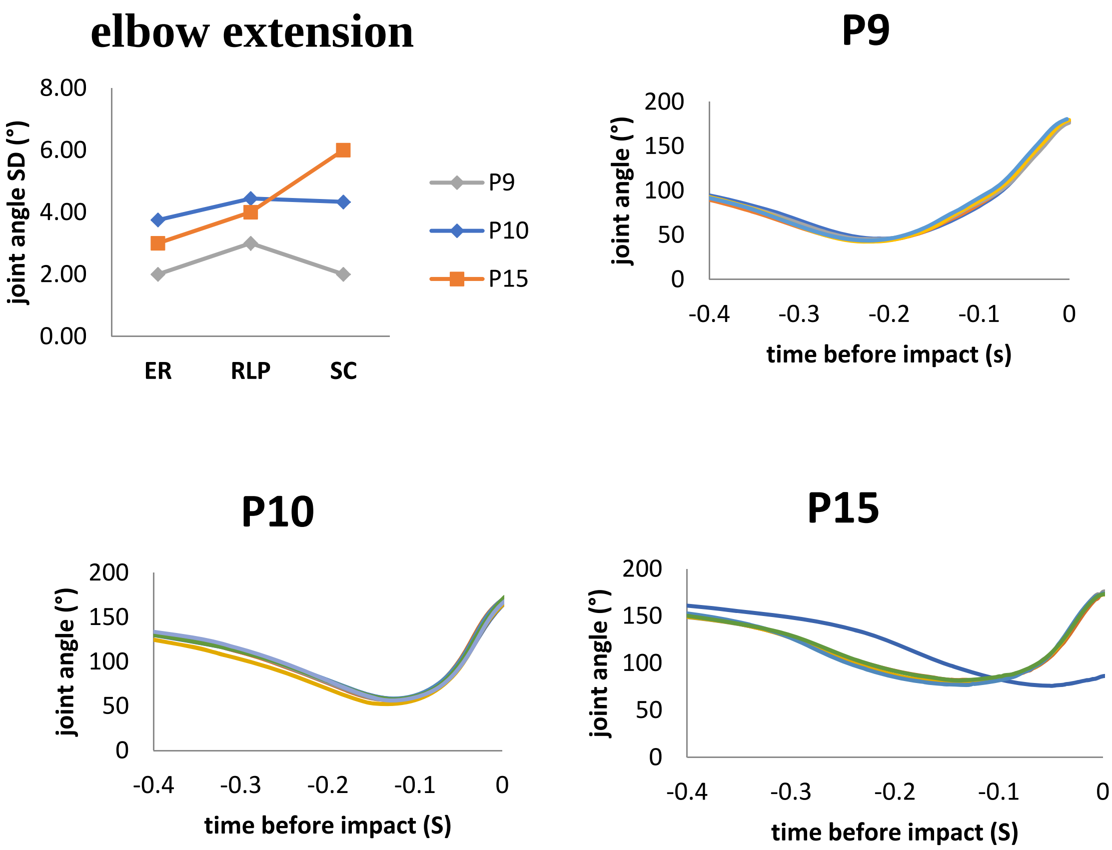


Figure 8.6 – SD of elbow extension and flexion through the key instants; elbow extension and flexion of all trials plotted.

Examination of the variability data for the elbow flexion and extension angle reveals that there was a similar pattern between the three participants. Although similar the results show that P15, who was the participant with the highest variability of service speed, flexed their elbow a shorter amount of time compared to our other two participants (Figure 8.6).

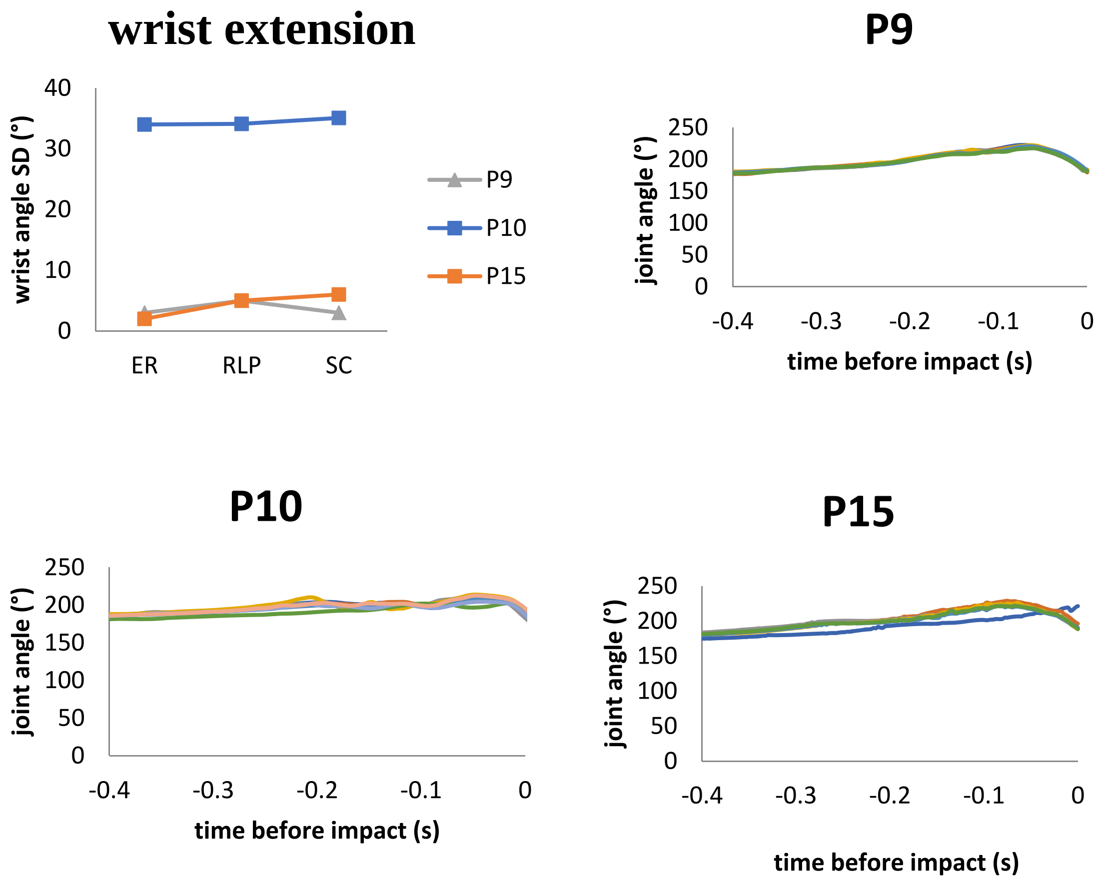


Figure 8.7 – SD of wrist extension and flexion through the key instants; wrist extension and flexion of all trials plotted.

Examination of the variability data for the wrist flexion and extension angle reveals that there was a similar pattern between the three participants. All participants remained static before extending the wrist before ball contact (Figure 8.7).

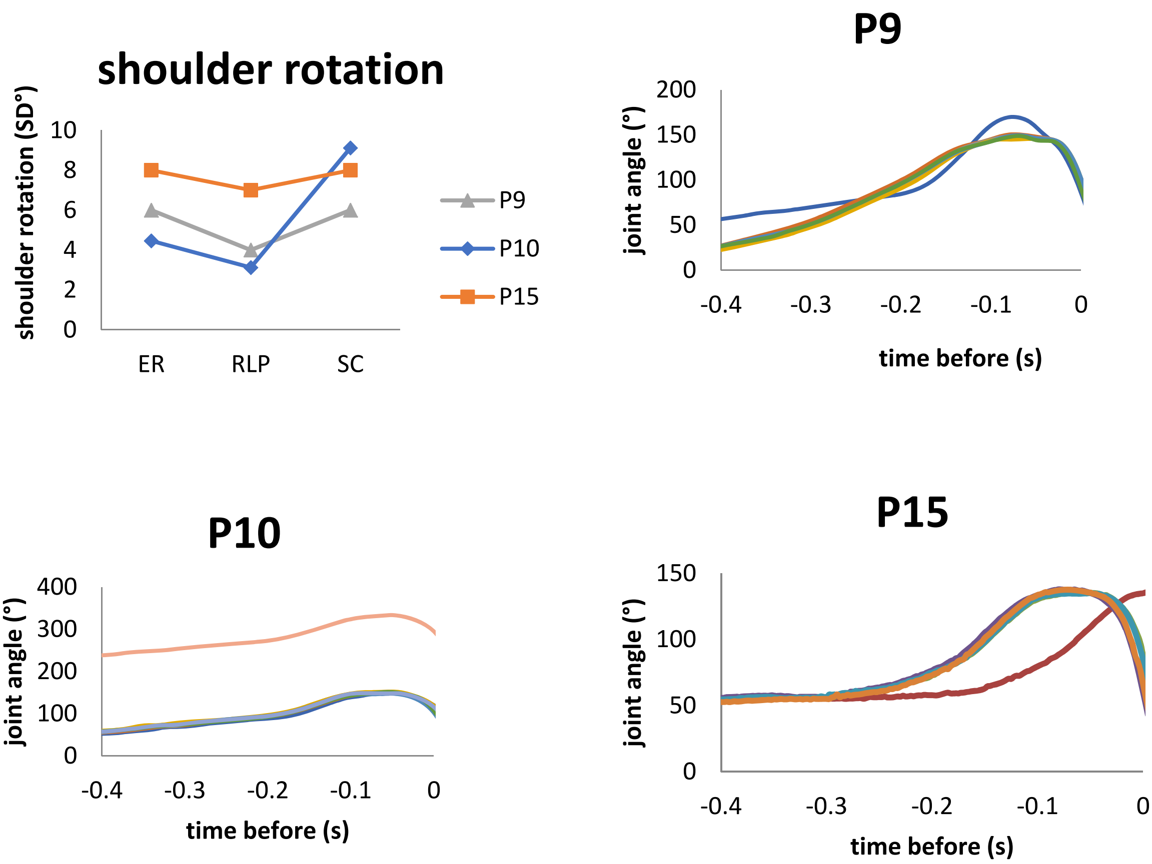


Figure 8.8 – SD of shoulder rotation through the key instants; shoulder rotation of all trials plotted.

Examination of the variability data for the shoulder rotation reveals that there was a similar pattern between the three participants. However, the low (P9) and high (P15) variable participants had a greater range of motion for shoulder rotation compared to the participant with average speed variability (Figure 8.8).

The results show that the participant with the higher variability (P15) also had on average the longest amount of time moving through the prep phase of the tennis serve to the point of contact (Table 8.6).

Table 8.6 – Timing average and standard deviation between phases for participants with low, middle, and high-speed variability.

Participant	Prep – ER	Prep – SC	ER – SC	RLP – SC
P9	0.15 ± 0.02	0.34 ± 0.01	0.19 ± 0.01	0.12 ± 0.00
P10	0.09 ± 0.03	0.29 ± 0.02	0.20 ± 0.01	0.13 ± 0.02
P15	0.25 ± 0.03	0.41 ± 0.02	0.16 ± 0.01	0.11 ± 0.00

8.4 Discussion

The purpose of this study was to examine movement variability in the tennis serve. Many differences in technique, speed, and movement timings have been identified. Examination of variability data for three kinematic data for three participants of varying degrees of speed variability was examined in further detail.

The tennis serve speed of all participants when hitting down the left centre court line ranged from 91 – 164 mph (128 ± 52 mph). The results also showed that the participants hit the tennis serve in between 25 - 80% (38% ± 52%) when hitting to that location.

The tennis serve speed of all participants when hitting in the direction of the advantage court was between 81 – 129 mph (105 ± 34mph). The results also show that the participants hit the tennis serve in 38 – 88% (39% ± 61%).

The tennis serve speed of all participants when hitting in the direction of the right centre court line had a speed range of 95 – 127 mph (111 ± 27mph). The results also show that the participants hit the tennis serve in 33 – 100% (47% ± 67%).

The tennis serve speed of all participants when hitting in the deuce court direction was between 88 – 118 mph (103 ± 21). The results also showed that the participants had a range of 30 – 100% (47 ± 67%) of hitting the serve in for this direction.

The participants tended to hit towards the middle of the racket no matter which direction they were serving in. This could be the ‘sweet’ spot for the ideal placement of ball on the racket at impact for the best results for speed and accuracy.

Three participants were chosen for further analysis based on their variability in terms of tennis serve speeds while hitting in the left centre court line. Analysis of the data showed that for the three participants there was little difference in tennis location on the racket at impact. The participants were asked to hit the tennis ball as hard and as accurately as they could down the left centre court line.

The results show that the more consistent participant had a lower average speed compared to the other two participants. The participant also had a lower percentage of successful tennis serves being in (57%). One possibility that may account for the variation in speeds between the three participants is the speed - accuracy trade-off. The more consistent participant 9 may have decided to focus more on accuracy than speed when doing the service action. This is also supported when we look at participant 15's average speed and variability for the left centre court line. While P15 did have the highest average speed of the three participants, he also had the highest variability of speed along with one of the lowest percentage of successful serves.

All participants had a similar pattern for elbow extension and flexion throughout the tennis serve. The participants flexed the elbow before extending it prior to impact. The participant with the highest overall speed variability took a shorter amount of time to flex their elbow prior to contact. Therefore, it is reasonable to assume that the participants who took longer flexing their elbow used the time to position their forearm for the most desirable placement that would give them the desired results. Wrist extension and flexion data showed that the participants remained static before extending then flexing prior to impact.

Although the players had a similar pattern of shoulder rotation throughout the tennis serve, both the players with low and high variability had more range of motion throughout the movement compared to the average player.

The results show that the participant with the higher variability (P15) also had on average the longest amount of time moving through the prep phase of the tennis serve to the point of contact.

8.5 Conclusion

This study has investigated movement variability among elite tennis players. Differences in variability between a less, average, and more consistent player has been identified. Differences in body placement and movement timings could be identified for all players. Although further work is needed to understand the full extent of movement variability and speed trade off this investigation provides a basis for further study.

CHAPTER 9: COMPARSION OF TECHNIQUE IN THE BADMINTON JUMP SMASH AND TENNIS SERVE

9. 1 Introduction

Two of the major racket sports include badminton and tennis. Racket sports have provided a vehicle for investigating fast interceptive actions and multi-segment interactions within the racket arm during performance shots (Lees, 2008).

In badminton the most commonly used aggressive stroke is the overhead smash. It is the standard of execution of this stroke that determines the advantage of the one player over another. Abe and Okanoto (1989) and Lo and Stark (1991) have pointed out that the power and speed of the badminton smash is what makes it a powerful offensive weapon. Lo and Stark (1991) also showed that skilled players are characterised by the great speed and precision of their smash stroke. The fastest badminton smash during competition has been recorded at 206 mph.

Like the badminton smash, the tennis serve is one of the most effective weapons a player has during a match. The success of a powerful serve depends on the speed, control, and spin of the ball. Especially important is the speed of the ball after impact, so speed of the racket at impact is central to a powerful serve. The fastest tennis serve during competition was recorded in 2012 at 163.7 mph.

Although these sports may be similar in nature there are a number of factors that can cause a difference in outcome. The ball or shuttlecock size and weight, racket size, and string tension can all play a role in a player's technique.

The aim of this study is to compare the performance technique between a badminton player and a tennis player. This study will identify the technique factors that contribute to the participants to producing high post impact speeds and the differences between their respective sports.

9.2 Methodology

9.2.1 Participants

One male badminton and one male tennis player (mean ± standard deviation: age 24.6 ± 6.4 years; height 1.83 ± 0.08 m; body mass 79.0 ± 0.0 kg) participated in this investigation. Each player performed twenty-four maximum velocity jump smashes and tennis serves respectively which were recorded using 18 camera Vicon Motion Analysis System (OMG Plc., Oxford, UK), operating at 400 Hz. The camera set-up was positioned to include the half of the court that the participant was performing in, approximately 7 x 6 x 3 m. No participants were aware of any injury/illness that would have affected their performance within the testing protocol. The testing procedures were explained to each participant in accordance with Loughborough University ethical guidelines and an informed consent form was signed. All participants conducted a thorough warm-up prior to the start of the data collection.

9.2.2 Analysis

Initially mean and standard deviation values were calculated for each variable. A simple visual inspect was carried out on the data. While this lacks the scientific rigour of a statistical test, it was thought to be suitable in this case in order to compare the outcomes of the participants.

9.3 Results

Looking at the two fastest participants in the tennis and badminton study we see that the participants had a post impact speed of 126 mph – 235 mph respectively. Details of the range, mean, and standard deviation of each calculated technique parameter for both of the participants are provided in Table 9.1 along with a visual comparison (Figure 9.1)

Table 9.1 – Details of the tennis and badminton, mean and standard deviation for each parameter calculated.

technique parameter	Tennis	Badminton
ball speed	126 mph	235 mph
knee extension; prep	107°	107°
trunk rotation; ER	16°	25°
trunk rotation; BC	-11°	8.36°
trunk extension; ER - BC	207°	208°
trunk flexion; ER - BC	183°	187°
trunk lateral flexion; max, ER - BC	18°	20°
shoulder ext rotation max, ER - BC	62°	113°
shoulder internal rotation; ER - BC	-19°	-34°
shoulder abduction; ER - BC	51°	44°
elbow extension angle; ER	69°	70°
elbow extension angle; BC	189°	163°
elbow pronation; ER	-63°	-95°
elbow pronation; BC	-55°	-74°
elbow pronation; ER - BC	-8°	20°
elbow pronation; max, ER - BC	-49°	-76°
elbow pronation; min, ER - BC	-77°	-129°
wrist extension; ER	203°	286°
wrist extension; BC	184°	262°
timing; Prep to BC	0.39 s	0.60 s
timing; Prep to ER	0.22 s	0.52 s
timing; ER to BC	0.17 s	0.09 s

Note: prep: preparation; ER: end of retraction; BC ball contact

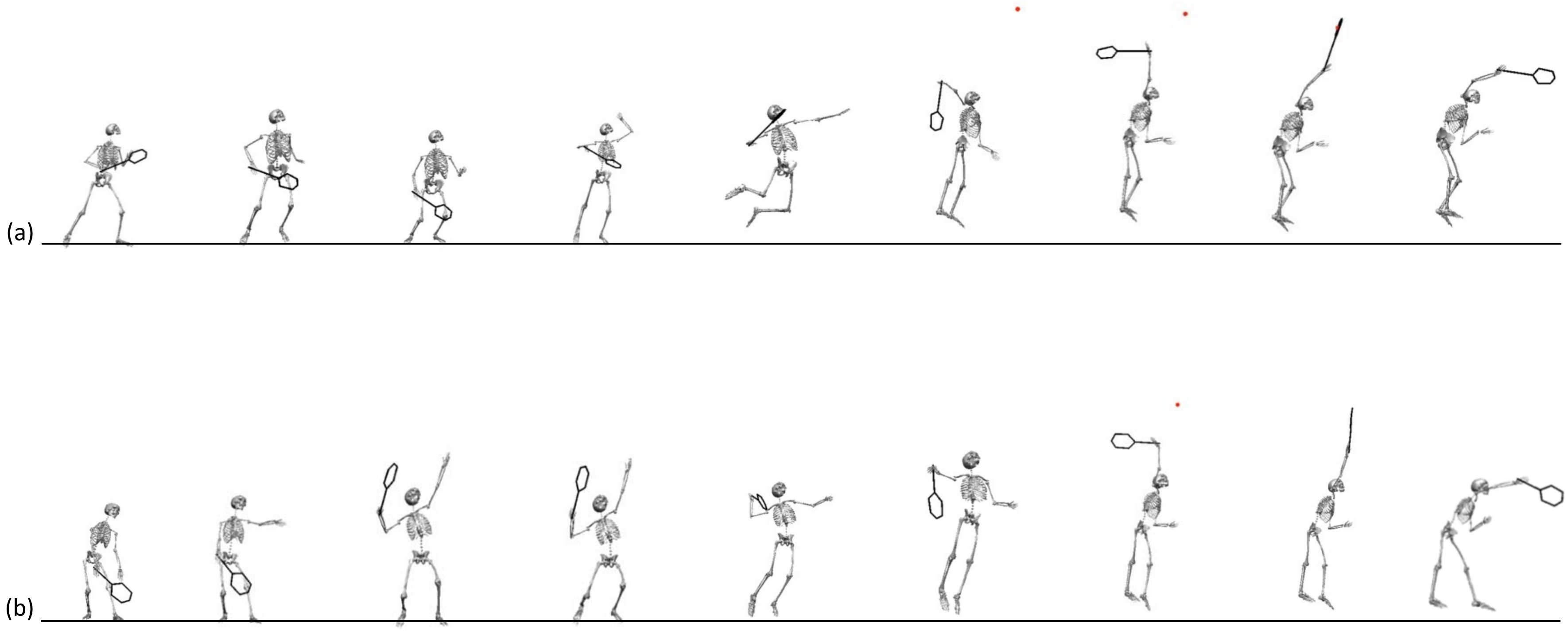


Figure 9.1 – Comparison of (a) badminton and (b) tennis participants throughout their sporting action.

Visual inspection of the participants at key instants in the badminton jump smash and tennis serve shows some differences in technique between our players. During the preparation phase, while both players had a knee extension angle of 107°. The trunk position for the badminton player is more forward than that of the tennis player.

During the instant of ER both players are leaning back ready to continue the forward swing of the sporting action. The tennis player has less trunk rotation at this moment that that of the badminton player. The tennis player also has a slightly lower elbow and wrist extension angle than that of the badminton player at this point in their sporting action.

At the moment of the racket lowest point we can see that the badminton player trunk is extended forward more than that of the tennis player. At contact both players are leaned forward in their sporting action to generate the momentum needed to complete the task, although the badminton player has a slightly higher trunk flexion than that of the tennis player. The badminton player also has more knee bend throughout their action where the tennis player has more of a straight leg. At contact the tennis player elbow is relatively more up than that of the badminton player, who has the elbow flexed more towards the shuttle.

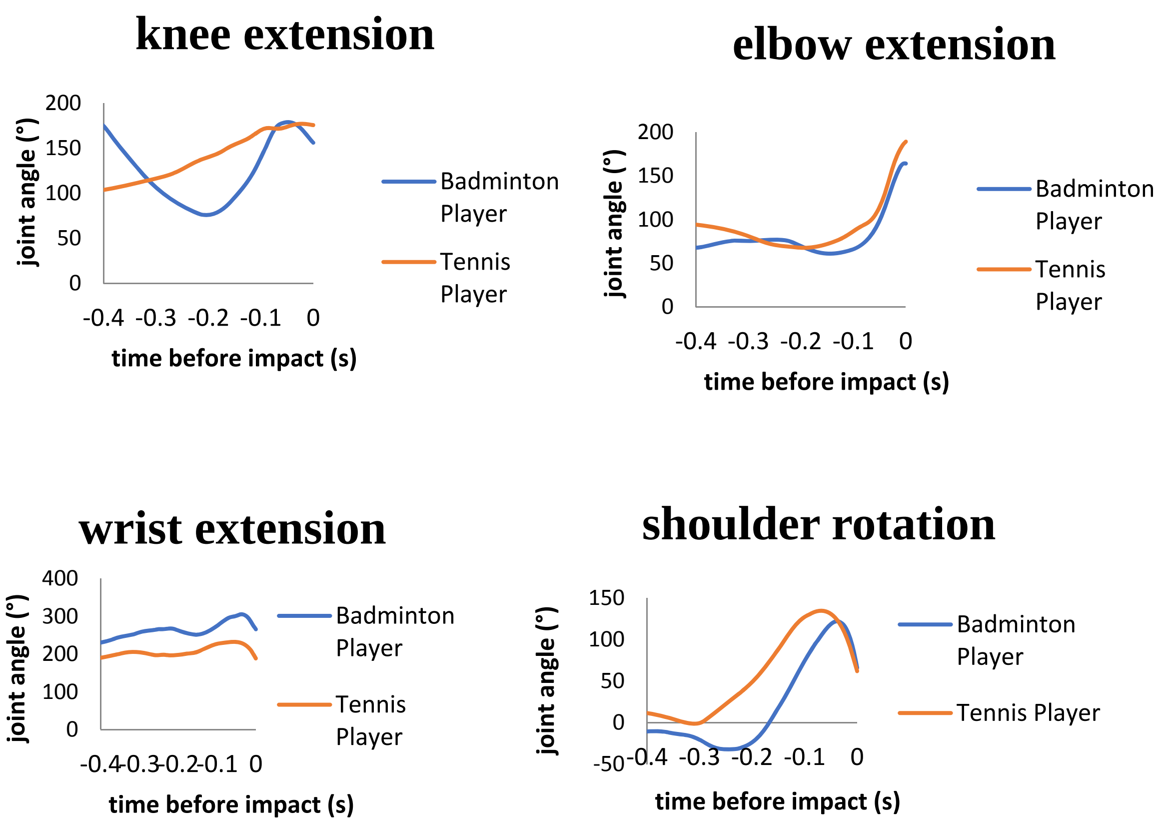


Figure 9.2 – Comparison of the knee, elbow, wrist, and shoulder movements for the badminton and tennis player throughout the sporting action.

When looking at the knee action .4 seconds before impact between the two players we can see differences. The tennis player knee starts slightly flexed before extending before impact while the badminton player tends to have deeply flexed knee before extending it at contact.

The pattern of elbow flexion and extension was similar for both players although the tennis player extended a little bit more than the badminton player just before impact. The shape of the wrist again was similar for both players, although the badminton player angle remained relatively static before the wrist flexed, whereas the tennis player extended their wrist prior to impact.

The badminton player has more range of motion for the shoulder compared to that of the tennis player. For the shoulder the badminton player first has a slight internal rotation before externally rotating before going into the final rotation prior to impact.

9.3 Discussion

Previous studies have reported correlations between technique and speed for the badminton jump smash and the tennis serve; however few compared the differences between the two. This study uses kinematic data in order to account for the differences between the badminton jump smash and the tennis serve actions. The results of this study suggest that there are key differences within technique between the two sporting actions especially in knee extension, trunk rotation, shoulder rotation and timing.

The results show that there is a difference in the speed of the badminton jump smash compared to that of the tennis serve. This can be the result of the lighter racket and shuttlecock used in the badminton jump smash. By having a lighter racket and shuttle badminton players can move through the sporting action quicker while producing the momentum needed for a high velocity smash.

While both players had a knee extension angle of 107° the visual inspection of the participants shows that the players had very different stances during this point in the action. The badminton player at this key instant had a wider foot ready stance while the tennis player had both legs closer together. Also, at this point in time the tennis player trunk was tilted backwards more than the badminton player in preparation for the ball. The badminton player's trunk at this instant is more forward as they are ready to attack the shuttle from the opposing player.

At the ER key instant, we can also see more contrast in the body position for the two participants during their respective actions. While both players are leaning backwards at this point in the action, the tennis player has a smaller degree of trunk extension at this phase compared to the badminton player.

The shoulder position for the tennis player is more horizontally abducted at this position compared to that of the badminton player. However, the badminton player shows more shoulder rotation throughout the phases. The bigger range of motion that occurs for the badminton player within the shoulder action during the badminton jump smash put their elbow and wrist in the desired position for a fast smash.

The elbow and wrist data shows that tennis has a smaller range of motion than that of the badminton player. Timing between the phases shows that a tennis player move faster through the general action from preparation to contact than that of the badminton player however, when looking directly at the ER-BC phase the badminton player had a faster time. This could be because the badminton racket is much lighter compared to the tennis racket. Also during this time the tennis player must make a full loop to get in the correct position to hit the ball for the service action were as the badminton player tends to more of a flick and wrist snap action to complete the jump smash. In essence, the tennis player has a greater range to cover than that of the badminton player.

Differences in the size and of the racket and ball verse the racket and shuttle are also thought to play a role in the differences of speed for the two sporting actions. The racket and shuttle are lighter than that of the tennis racket and ball. By having a lighter racket players do not have to use as much energy to move it through the air. Also, the lighter badminton racket can move faster than that of the heavier tennis racket. By having the racket move faster, this will provide the player a greater chance of hitting the shuttle quicker than of the slower tennis racket.

Although the tennis participant is taller than that of the badminton participant, the badminton participant jumps higher when performing the smash. This difference in jump height can play a part in the difference of post impact speeds between the two participants. By jumping higher, the badminton participant have a lager range of motion in the shoulder to hit the shuttle through. It is this range of motion that can help the transfer of energy and momentum needed for higher smash speeds.

9.4 Conclusion

This study has identified the differences between the badminton jump smash and the tennis serve techniques. The results suggest that while the two sporting actions have similar movements there are key differences in the techniques. Badminton players have a wider foot stance during the preparation phase than that of a tennis player. Also, a badminton player has a greater trunk rotation throughout their sporting action that than of a tennis player. While tennis player may complete the tennis service action faster than that of badminton jump smash, when looking at the critical time before impact we see that the badminton player moves through this phase quicker. This could be because of the lightness of the badminton racket compared to a tennis racket and the differences in the range of motion that the shoulder, elbow, and wrist are undergoing through this phase.

The results of this investigation are likely to be very useful in the coaching and studying racket sports technique. Future studies should look at the differences in racket and jump height and how they affect any differences in outcome between the two sports.

CHAPTER 10: SUMMARY AND CONCLUSIONS

The purpose of the present study was to analyse the badminton jump smash and tennis serve actions in order to gain an understanding of the interactions between aspects of technique, speed, and variability. Within this chapter, the extent to which this aim has been achieved through the development and application of a multi-segment representation of the participant is considered. The methods used within the study are also summarised and limitations and potential improvements are identified. The research questions posed in Chapter 1 are addressed and potential future studies are proposed.

10.1 Thesis Summary

10.1.1 Data Collection

Data were collected for a group of badminton and tennis players in an indoor practice facility (Sections 3.1.1 and 3.1.2). Each participant performed maximum speed badminton jump smashes or tennis serves. A Vicon Motion Analysis System was used to collect synchronous kinematic (400 Hz) for each trial performed. A marker on the shuttle and six markers on the tennis ball enabled post impact speeds to be calculated.

Small sample sizes are a problem when studying elite populations. Subject-specific segmental inertia parameters were determined using the geometric model of Yeadon (1990) (Section 3.5). The model has been used successfully in previous studies (Wilson, 2003; Glynn, 2007), enabling subject specific parameters to be determined with little inconvenience caused to the subjects.

10.1.2 Data Processing

The best trials – maximum speed with minimal marker loss were identified for each participant for inclusion in this study. Although every effort was made to reduce noise of the data, the dynamic nature of both the badminton jump smash and tennis serve actions meant there were some gaps in the tracked marker positions. These gaps were small and were filled using one of the selection methods, depending on the situation (Section 3.6.2).

Some noise within the kinematic data collected using a marker based motion tracking system occurred. This can be the consequence of marker wobble due to skin movement or the system failure to track all the markers accurately at every point during the jump smash or the tennis serve. Although the marker trajectories were relatively smooth, this noise was magnified when differentiated in order to calculate speed and accelerations. All kinematic data were filtered using a Butterworth filter (double-pass) with a low pass cut-off frequency of 30 Hz (Section 3.6.3).

10.2 Data Analysis

A whole-body analysis of both the badminton jump smashes and the tennis serve was performed within Vicon's BodyBuilder software (Section 4.1). The human body was represented as a system of 18 rigid segments: head and neck; upper back; lower back; pelvis; 2 x humerus; 2 x radius; 2 x femur; 2 x tibia; and 2 x two - segment foot. Joint centres were located using a predictive approach, typically the mid-point of two strategically placed markers (Section 4.3). To reduce errors in the location of the joint centres, markers were positioned when the participant was in a typical position as occurs during the sporting action – e.g. arm overhead when positioning the shoulder markers. A three-dimensional local coordinate system was defined for each segment, allowing segment orientations and joint angles to be calculated (Section 4.5).

The mass, position of the centre of mass and the three principal moments of inertia of each segment were defined using the output from the geometric model of Yeadon

(1990) for each participant (Section 4.6). This enabled the calculation of the whole body centre of mass for each participant and the subsequent calculation of the forces and moments acting at each joint.

Parameters describing aspects of sporting technique were calculated for each trial (Section 4.7.2), these included: knee extension, trunk rotation and flexion, shoulder rotation, elbow and wrist flexion and extension, and elbow and wrist pronation.

Correlations were assessed using a two-tailed Pearson's product moment coefficient and the effect of interactions between technique parameters on a particular outcome measure were assessed using linear regression. A limitation of this approach was the relatively small sample size included in this study, which restricted the number of predictive parameters which could be identified. However, the results obtained explain the majority of the variation in each outcome measure and give an indication of the mechanics of the badminton jump smash and tennis serve actions. It should be noted that this study has addressed linear relationships between technique variables; future work could consider the possibility of other forms of associations.

Research Questions

The research questions posed in Chapter 1 were addressed in detail in Chapters 5-9. The full body analysis performed enabled the mechanics of the badminton jump smash and the tennis serve to better understood. The research questions are restated below and the results are summarized.

1. *Which kinematic technique aspects of the badminton smash explain the most variance in smash speed.*

Previous studies have reported correlations between shuttlecock velocity after impact and a variety of different elements of the badminton jump smash technique. There is currently no consensus as to which aspects of the technique are the most important in terms of determining shuttlecock jump smash. This study used stepwise linear regression in order to account for interactions between technique parameters with the aim of identifying the key variables that determines shuttlecock velocity after impact that accounted for 83.7% of shuttle velocity. The results of this investigation suggest the main variations in shuttlecock velocity after impact among badminton players can be explained by using three technique parameters; elbow extension angle at the end of retraction key instant, wrist extension angle at shuttle contact, and timing between preparation and shuttle contact. The analysis performed will enable those aspects of technique which best characterise the fastest tennis players to be identified and the mechanics by which the players generate pace to be more thoroughly understood.

2. *What are the relationships between outcome and technique variability in the badminton jump smash?*

The purpose of this study was to examine movement variability in the badminton jump smash. A number of differences technique, speed, and movement timings have been identified. Examination of variability data for four kinematic variability data for three participants of varying degrees of speed variability was examined in further detail.

Any differences shown with the analysis of the data would be down to the participants' technique and not due to the coach serve of the shuttlecock. This can be seen as soon as the participants prepare for take-off before impact. The significant difference reflected in the analysis could be because of the different approaches that the participants took into order to position the body in order to perform the jump smash. Upon inspection of the data it could be seen that some participants tended to move their feet more than others when preparing to perform the smash.

The data showed that the female participants tended to have a straighter knee throughout the jump smash compared to the male participants. The male participants also tended to flex their knee mid-jump prior to impact, while the females did not. The bending of the knee in mid-jump allows for a participant to gain more forward momentum for the smash movement and therefore allowing for a harder hit of the shuttlecock at impact.

All participants had a similar pattern for elbow extension and flexion throughout the jump smash, however the more consistent player tended to extend the elbow before flexing it prior to impact. Wrist extension and flexion data showed that our participants who had average and more consistent speeds in their smash extended their wrist before flexing it prior to impact. The less consistent player remained static throughout the smash before flexing the wrist.

Although all participants had a similar pattern in shoulder rotation during the jump smash the participant with average consistency remained static prior to rotating their shoulder compared to the less consistent and more consistent participants.

The movement timings between the players showed significant difference between the participants in the end of retraction to shuttle contact phase. It is interesting that the participant with the lowest consistency in smash speeds had the fastest times during these phases. It could be said that longer times within these phases allows for a participant to judge the shuttle better, therefore getting in a better position to hit the smash harder. The analysis performed will enable those aspects of technique which best characterise the fastest badminton players to be identified and the mechanics by which the players generate pace to be more thoroughly understood.

3. Which kinematic technique aspects of the tennis serve explain the most variance in speed for the tennis serve in four directions?

In a tennis serve speed is one of the main factors in determining if a serve will be successful or not and has been the focus of a number of previous investigation. Many studies have identified individual aspects of tennis serve technique, which characterise the fastest serves. However, none of the studies have taken into consideration how individual technique parameters interact with one another during an optimal serve in four different directions. For the left and right centre court line the research showed that there was no variable that was significantly related to serve speed. When the players hit in the direction of the advantage court trunk rotation; racket lowest point explained 23.8% of the variation in ball speed. The results also showed that when the players hit to the deuce court that timing: end of retraction – ball contact phase explained 33.6% of ball speed. The analysis performed will enable those aspects of technique which best characterise the fastest tennis players to be identified and the mechanics by which the players generate pace to be more thoroughly understood.

4. *What are the relationships between outcome and technique variability in the tennis serve?*

By comparing tennis serves down the left centre court line variability in the participant's technique was able to be analysed. The results showed that tennis players on average hit the ball in the centre of the racket no matter which direction of the court they were aiming for. The more consistent player in terms of more successful serves tended to hit the serve slower than the other players. The analysis performed will allow the interactions in a successful and unsuccessful serve to be investigated more thoroughly.

5. *How does the badminton smash technique compare with the tennis serve technique?*

Badminton and tennis are two of the most popular racquet sports today. With the badminton smash and tennis serve consisting of similar overarm techniques it is natural to want to compare the two actions and see how they may differ. Research showed that from the beginning of the respective sporting technique differences in technique could be seen. The badminton player used more of an attack stance compared to that of the tennis player who had more trunk tilt at this point in time. The shoulder position for the tennis player is more horizontally abduction than that of the player; however the badminton shows more shoulder rotation throughout the phases. The elbow and wrist data showed more range of motion for the tennis player compared to that of the badminton player. The differences in racket and weight of the shuttle verse tennis ball is also thought to play a part in the variation of speed between the two sports. The badminton racket and shuttle is lighter than that of the tennis racket and ball. It is this lightness that is thought to allow the badminton player to move the racket faster through the air. By moving the racket faster this allows for the badminton player to have more momentum when hitting the smash. The analysis performed will enable those aspects of technique which best characterise the fastest tennis players to be identified and the mechanics by which the players generate pace to be more thoroughly understood.

10.3 Future Studies

Additional research questions that are promoted by the work in this thesis include:

- How does international level badminton players' technique differ with that of county level players?
- How do male and female badminton players' techniques differ?
- How do male and female tennis players' techniques differ?
- In what ways does ball toss, toss location, racket size, and jump height affect tennis serve speeds?
- In what ways does shuttle location, jump height, racket size affect badminton smash speeds?

10.4 Conclusion

The aim of the present study was to analyse the badminton jump smash and the tennis serve sporting actions in order to gain an understanding of the mechanics of the movement, especially how aspects of the sporting technique affect post impact speed. To achieve this, a three-dimensional analysis was performed on a group of badminton and tennis. It was found that in the badminton jump smash 83.7% of shuttle speeds could be explained by elbow extension at the end of retraction key instant, wrist extension at shuttle contact, and the timing it take for a player to move between the preparation – end of retraction phase. The data also showed that more consistent badminton player extended their elbow being flexing it prior to impact. Timing was also shown to play a part in badminton speed variability. The subject who had less variability in shuttle speeds took a longer amount of time to move through the jump smash phases.

In the tennis serve the data showed that there was no significant difference when hitting down the left and right centre court line. When subjects hit toward the advantage court the best predictor of speed was the trunk rotation angle taken between the racket lowest point through the shuttle contact phase, explaining 23.8% of speed variation. When hitting towards the deuce court the strongest indicator of speed was the time it took for the subjects to move between the end of retraction phase through to ball contact, explaining 33.3% of speed variation. Tennis variability data showed that players tended to hit the ball near the centre of the racket. The data also showed that the subject who was more consistent in their service speeds had lower speeds than the other subjects. This hints that the subject possibly choose to consistency over speed when hitting the tennis serve.

Comparisons between the badminton jump smash and the tennis serve show that badminton players have greater trunk rotation throughout their sporting action that that of tennis players. Although tennis players move through the total action quicker, when it comes to moving through key phases badminton players are quicker. This could be because of the lighter racket and shuttle compared to that of the tennis racket and ball.

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APPENDIX 1: SUBJECT DETAILS

Study 1

Participant	Height (m)	Mass (kg)
1	1.85	71.4
2	1.80	80.0
3	1.88	79.0
4	1.88	69.0
5	1.81	79.3
6	1.75	69.9
7	1.91	83.3
8	1.78	70.0
9	1.81	67.5
10	1.85	80.6
11	1.76	80.2
12	1.91	82.1
13	1.79	64.1
14	1.89	76.9
15	1.78	63.9
16	1.79	88.8
17	1.81	71.9

Study 2

Participant	Height (m)	Mass (kg)
1	1.91	79.0
2	1.67	69.2
3	1.81	94.3
4	1.86	83.0
5	1.71	73.1
6	1.79	72.9
7	1.69	58.3
8	1.63	67.1
9	1.77	79.0

Study 3 and Study 4

Participant	Height (m)	Mass (kg)
1	1.85	71.4
2	1.80	80.0
3	1.88	79.0
4	1.88	69.0
5	1.81	79.3
6	1.75	69.9
7	1.91	83.3
8	1.78	70.0
9	1.81	67.5
10	1.85	80.6
11	1.76	80.2
12	1.91	82.1
13	1.79	64.1
14	1.89	76.9
15	1.78	63.9
16	1.79	88.8
17	1.81	71.9

APPENDIX 2: CONSENT FORMS

Loughborough University

Biomechanical Factors in Badminton Smash that Determine Shuttle Velocity

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name ______________________________

Your signature ______________________________

Signature of investigator ______________________________

Date ______________________________

PRE-SELECTION MEDICAL QUESTIONNAIRE

LOUGHBOROUGH UNIVERSITY

SCHOOL OF SPORT, EXERCISE, AND HEALTH SCIENCES

Please read through this questionnaire, BUT DO NOT ANSWER ANY OF THE QUESTIONS YET. Assistance will be provided if you wish to discuss any questions on this form. When you have read right through, there may be questions you would prefer not to answer. In this case please tick the box labelled “I wish to withdraw” below. Also tick the box labelled “I wish to withdraw” if for any other reason you do not wish to take part.

	Tick appropriate box
I wish to withdraw	☐
I am happy to answer the questionnaire	☐

Loughborough University

Name/Number ………………….

Health Screen Questionnaire for Study Volunteers

Note to Investigators: This HSQ can be used in its entirety but you can also remove some of the questions if you know they are not relevant to your study.

As a volunteer participating in a research study, it is important that you are currently in good health and have had no significant medical problems in the past. This is (i) to ensure your own continuing well-being and (ii) to avoid the possibility of individual health issues confounding study outcomes.

If you have a blood-borne virus, or think that you may have one, please do not take part in this research ***[only include for projects involving invasive procedures].***

Please complete this brief questionnaire to confirm your fitness to participate:

1. **At present,** do you have any health problem for which you are:

(a) on medication, prescribed or otherwise .... Yes ☐ No ☐

(b) attending your general practitioner .... Yes ☐ No ☐

(c) on a hospital waiting list.. Yes ☐ No ☐

2. **In the past two years,** have you had any illness which required you to:

(a) consult your GP .... Yes ☐ No ☐

(b) attend a hospital outpatient department .... Yes ☐ No ☐

(c) be admitted to hospital .... Yes ☐ No ☐

3. **Have you ever** had any of the following:

(a) Convulsions/epilepsy .... Yes ☐ No ☐

(b) Asthma .... Yes ☐ No ☐

(c) Eczema .... Yes ☐ No ☐

(d) Diabetes .... Yes ☐ No ☐

(e) A blood disorder .... Yes ☐ No ☐

(f) Head injury .... Yes ☐ No ☐

(g) Digestive problems .... Yes ☐ No ☐

(h) Heart problems .... Yes ☐ No ☐

(i)	Problems with bones or joints	Yes	☐	No	☐
(j)	Disturbance of balance/coordination	Yes	☐	No	☐
(k)	Numbness in hands or feet	Yes	☐	No	☐
(l)	Disturbance of vision	Yes	☐	No	☐
(m)	Ear / hearing problems	Yes	☐	No	☐
(n)	Thyroid problems	Yes	☐	No	☐
(o)	Kidney or liver problems	Yes	☐	No	☐
(p)	Allergy to nuts	Yes	☐	No	☐

4. Has any, otherwise healthy, member of your family under the

age of 35 died suddenly during or soon after exercise? . Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (eg to confirm problem was/is short-lived, insignificant or well controlled.)

....
....

5. Allergy Information

(a)	are you allergic to any food products?	Yes	☐	No	☐
(b)	are you allergic to any medicines?	Yes	☐	No	☐
(c)	are you allergic to plasters?	Yes	☐	No	☐

If YES to any of the above, please provide additional information on the allergy

………..

6. Additional questions for female participants

(a)	are your periods normal/regular?	Yes	☐	No	☐
(b)	are you on "the pill"?	Yes	☐	No	☐
(c)	could you be pregnant?	Yes	☐	No	☐
(d)	are you taking hormone replacement therapy (HRT)?	Yes	☐	No	☐

7. Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.

Name: …….

Telephone Number: ……………………………………………………………………………………………………….

Work ☐ Home ☐ Mobile ☐

Relationship to Participant:…………………………………………………………………………………….........

8. Are you currently involved in any other research studies at the University or elsewhere?

Yes ☐ No ☐

If yes, please provide details of the study

………
………

Biomechanical Factors in Badminton Smash that Determine Shuttle Velocity

Adult Participant Information Sheet

Investigator Contact Details:
Romanda Miller – UU 1.13. R.Miller@lbroro.ac.uk
Dr Mark King – UU. 1. 08 - M.A.King@lboro.ac.uk

What is the purpose of the study?
The aim of this research is to examine the biomechanical factors of a badmintons mash and determine why some serves are successful and others are not.

Who is doing this research and why?
This study is part of a PhD research project examining the biomechanics of the tennis serve conducted by the sports biomechanics research group.

Are there any exclusion criteria? The participants will have played tennis for five years and no injuries within the last 3 months.

What will I be asked to do?
The participant will be asked to be fitted with reflective markers and perform a flat tennis serve 20 times while being captured by the high speed camera system.

Once I take part, can I change my mind?
Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

What personal information will be required from me?
A general health information sheet will be collected at the beginning of the study.

Are there any risks in participating?
There should not be any risks performing this task.

Will my taking part in this study be kept confidential?
All data collected in this study will remain confidential and secure. Participants will be allocated an identification number for recording and storage of data, and no participant will be referred to by name outside of data collection sessions, such as publication of the study.

What will happen to the results of the study?
All data collected conform to the university's guidelines on data collection and storage, and will therefore be stored securely in its original state for the duration of the collection, analysis and publication of the study.

Is there anything I need to bring with me?
You should bring your own racket.

What type of clothing should I wear?
Reflective motion markers will be placed on the skin, therefore shorts will be required for all testing sessions to allow placement of markers on the hip, trunk, and leg areas.

What do I get for participating?
Participants will be allowed ongoing feedback on performance in the tennis serve task throughout the time of the study; however, a detailed biomechical analysis of tennis serve performance will not be available until the research is completed.

I have some more questions; who should I contact?
Any questions regarding the testing procedures or tennis serve practice should be first addressed to Romanda Miller (R.Miller@lboro.ac.uk); alternatively, further queries may be addressed to Dr Mark King listed above.

If you have any concerns regarding your participation in this study, or the conduct of any of the investigators involved, please refer to the university policy relating to research misconduct at the following link:

http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

APPENDIX 3: MARKER POSITIONS

The marker positions used in this study are illustrated in the pictures below, details of the exact position of each marker are also provided.

HEAD

A head-band with four markers attached was placed over the subject's head; the front two markers were positioned on the temples. The positions of the two makers on the back of the head were not so critical, they were positioned so they were level when the subject's neck was straight.

PELVIS

Marker #	Marker Label	Marker Position
		For each of these markers, the marker centre should be positioned above the tip of the landmark
1	RASI	Bony protrusion of the right anterior super iliac
2	LASI	Bony protrusion of the left anterior super iliac
3	RPSI	Dimple created by the right posterior super iliac
4	LPSI	Dimple created by the left posterior super iliac
5	LHIP	Position not crucial (only used for asymmetry purposes). Roughly level with the other pelvis markers and approximately above the hip joint centre

THORAX

Marker #	Marker Label	Marker Position
6	LUM1	First lumbar vertebra. Can be located by initially finding L5, which lies between the two PSIS. From here you can count up to L1.
7	T10	Tenth thoracic vertebra. Can count up from L1 (T12, T11, T10).
8	STRN	Centre of marker positioned over lower tip of sternum
9	CLAV	Centre of marker positioned over upper tip of clavicle
10	C7	Seventh cervical vertebra. This is the long cervical vertebra, which is particularly prominent when the subject bends their head forwards.
11	RBAK	Position not crucial, is just used for asymmetry. Somewhere in the centre of the right scapula

ARMS

Marker #	Marker Label	Marker Position
12, 13	SHOP	Posterior of shoulder.
14, 15	SHOA	Anterior of shoulder
		• *Mid point of the posterior and anterior shoulder markers should define the Shoulder Joint Centre when the arm is pointing vertically upwards. Typically the anterior marker will be significantly higher than the posterior marker.*
16, 17	SHOT	Top of shoulder, positioned on the acromion process
18, 19	ELBM	Medial side of elbow
20, 21	ELBL	Lateral side of elbow
		• *Mid point of the 2 elbow markers is the Elbow Joint Centre – this should be done with the elbow fully straightened – i.e. in the part of the elbow's range of motion we want to be most accurate* • *A line joining the 2 elbow markers should be at* ***ninety degrees*** *to the frontal plane of the Humerus*
22, 23	WRA	Thumb side of wrist.
24, 25	WRB	Little finger side of wrist.
		• *Mid point of the 2 wrist markers is the Wrist Joint Centre* • *A line joining the 2 wrist markers should be at* ***ninety degrees*** *the frontal plane of the Radius*
26, 27	HND	Back of hand, on the hand's longitudinal axis – the line between the Wrist Joint Centre and the Middle Finger. This marker should be positioned **2cm** below the middle base knuckle

LEGS

Marker #	Marker Label	Marker Position
28, 29	TOE	On the centre line of foot Marker's centre was **3cm** from tip of big toe
30, 31	MTPM	Medial side of the MTP joint
32, 33	MTPL	Lateral side of the MTP joint
		• *Mid point of the 2 MTP markers is the MTP Joint Centre* • *A line joining the 2 MTP markers should be at* ***ninety degrees*** *to the frontal plane of the Foot*
34, 35	ANKM	Medial side of ankle
36, 37	ANKL	Lateral side of ankle
		• *Mid point of the 2 ankle markers is the Ankle Joint Centre* • *A line joining the 2 ankle markers should be at* ***ninety degrees*** *to the frontal plane of the Tibia*
38, 39	HEE	Centre line of foot, placed on back of heel of shoe and at similar height to Toe marker
40, 41	KNEM	Medial side of knee
42, 43	KNEL	Lateral side of knee
		• *Mid point of the 2 knee markers is the Knee Joint Centre* • *A line joining the 2 knee markers should be at* ***ninety degrees*** *to the frontal plane of the Femur*

APPENDIX 4: BODYLANGUAGE CODE

{*Written by Paul Felton 2014 for Romanda Miller, based on Peter Worthington's code from 2008*}

{*THIS MODEL HAS BEEN ADJUSTED TO BE USED IN ANALYSIS IN RACKET SPORTS*}

{*ASSUMING THE RACKET HAS BEEN MODELLED THE SAME AS IN ROMANDA MILLER'S THESIS*}

{*This model calculates predicted joint centres, joint angles, internal forces and moments for an 18 segment model*}

{*Segments consist of: Head and neck; lower back; upper back; pelvis;*}

{* 2 x (humerus; radius; hand); 2 x (femur; tibia; 2-segment foot)*}

{*Subject specific parameters including mass, mass location and inertia values must be inserted in the .mp file*}

{*A static trial must be run and the new .mp file saved in order to process dynamic trials fully*}

{*---*}

{*Start of macro section*}

{*Macro's are subroutines which can be used to do repeatable tasks*}

{*=====================*}

```
macro REPLACE4(p1,p2,p3,p4)

{*Replaces a marker if as long as it is the trial for one frame, by calculating the distance from three other markers*}

s234 = [p3,p2-p3,p3-p4]

p1V = Average(p1/s234)*s234

s341 = [p4,p3-p4,p4-p1]

p2V = Average(p2/s341)*s341
```

```
s412 = [p1,p4-p1,p1-p2]
p3V = Average(p3/s412)*s412
s123 = [p2,p1-p2,p2-p3]
p4V = Average(p4/s123)*s123
p1 = p1 ? p1V
p2 = p2 ? p2V
p3 = p3 ? p3V
p4 = p4 ? p4V
endmacro

MACRO DisplayAxes( ASeg )
{*Displays the local coordinates for each segment*}

ASeg#O = ASeg(0)
ASeg#X = ASeg(0) + 50 * ASeg(1)
ASeg#Y = ASeg(0) + 50 * ASeg(2)
ASeg#Z = ASeg(0) + 50 * ASeg(3)
OUTPUT( ASeg#O, ASeg#X, ASeg#Y, ASeg#Z )

ENDMACRO



{*End of macro section*}
{*===================*}

{*-----------------------------------------------------------------------------------------------*}



{*Initialisations*}
{*==============*}
```

```
{*By placing marker names in optional points allows the code to run when that marker doesnt exist*}

OptionalPoints(RFHD,RBHD,LBHD,LFHD)
OptionalPoints(C7,T10,LUM1,CLAV,STRN)
OptionalPoints(LSHOP,LSHOA,LELBL,LELBM,LWRA,LWRB,LHAND)
OptionalPoints(RSHOP,RSHOA,RELBL,RELBM,RWRA,RWRB,RHAND)
OptionalPoints(RASI,LASI,RPSI,LPSI)
OptionalPoints(LKNEM,LKNEL,LANKL,LANKM,LMPTM,LMPTL,LHEEL,LTOE)
OptionalPoints(RKNEM,RKNEL,RANKL,RANKM,RMPTM,RMPTL,RHEEL,RTOE)
OptionalPoints(RACKET1,RACKET2,RACKET3,RACKET4,RACKET5,RACKET6,RACKET7,RACKET8)

{*Set Deadband, except for static trials*}
{*Deadband is used to overcome angles jumping when segments are inline with one another*}
If $Static<>1 Deadband = $Deadband EndIf

{*Define Global Coordinates*}
{*========================*}

Gorigin = {0,0,0}
Global = [Gorigin,{1,0,0},{0,0,1},xyz]
{*DisplayAxes(Global)*}

$MarkerDiameter=14

{*-------------------------------------------------------------------------------------------------------*}

{*Replace missing markers*}
{*use if the marker is present for some of the trial, but missing at some point*}

REPLACE4(RACKET4,RACKET5,RACKET6,RACKET7)
OUTPUT(RACKET4,RACKET5,RACKET6,RACKET7)
```

```
REPLACE4(RACKET8,RACKET3,RACKET2,RACKET1)
OUTPUT(RACKET8,RACKET3,RACKET2,RACKET1)

REPLACE4(LKNEM,LKNEL,LANKL,LANKM)
OUTPUT(LKNEM,LKNEL,LANKL,LANKM)

REPLACE4(RACKET1,RACKET2,RACKET3,RACKET4)
OUTPUT(RACKET1,RACKET2,RACKET3,RACKET4)

REPLACE4(RACKET2,RACKET3,RACKET4,RACKET5)
OUTPUT(RACKET2,RACKET3,RACKET4,RACKET5)

REPLACE4(RACKET5,RACKET6,RACKET7,RACKET8)
OUTPUT(RACKET5,RACKET6,RACKET7,RACKET8)

REPLACE4(RACKET3,RACKET4,RACKET5,RACKET6)
OUTPUT(RACKET3,RACKET4,RACKET5,RACKET6)

REPLACE4(RACKET2,RACKET3,RACKET8,RACKET7)
OUTPUT(RACKET2,RACKET3,RACKET8,RACKET7)

REPLACE4(LELBM,LELBL,LWRA,LWRB)
OUTPUT(LELBM,LELBL,LWRA,LWRB)

REPLACE4(RELBM,RELBL,RWRA,RWRB)
OUTPUT(RELBM,RELBL,RWRA,RWRB)

REPLACE4(RKNEM,RKNEL,RANKM,RANKL)
OUTPUT(RKNEM,RKNEL,RANKM,RANKL)
```

```
REPLACE4(LASI,RASI,LPSI,RPSI)

OUTPUT(LASI,RASI,LPSI,RPSI)


{*====================================================================================================*}

{*JOINT CENTRES & POSITIONS OF INTEREST*}

{*====================================================================================================*}



{*Calculating joint centres that are between two markers*}


RSHO=(RSHOP+RSHOA)/2

LSHO=(LSHOP+LSHOA)/2


RELB=(RELBM+RELBL)/2

LELB=(LELBM+LELBL)/2


RWRI = (RWRA+RWRB)/2

LWRI = (LWRA+LWRB)/2


RKNE = (RKNEM+RKNEL)/2

LKNE = (LKNEM+LKNEL)/2


RANK = (RANKM+RANKL)/2

LANK = (LANKM+LANKL)/2


RMTP = (RMPTM+RMPTL)/2

LMTP = (LMPTM+LMPTL)/2


OUTPUT (RSHO,LSHO,RELB,LELB,RWRI,LWRI,RKNE,LKNE,RANK,LANK,RMTP,LMTP)
```

```
{*-----------------------------------------------------------------------------------------------------*}

{*Calculate hip joint centres using Davis et al, (1991)*}

SACR = (LPSI+RPSI)/2
PELF = (LASI+RASI)/2

If $Static==1 Then {*Save average leg length as parameter*}
                LLegLength = DIST(LASI,LKNEL)+DIST(LKNEL,LANKL)
                RLegLength = DIST(RASI,RKNEL)+DIST(RKNEL,RANKL)
                MP_LegLength = (LLegLength+RLegLength)/2
                C = MP_LegLength*0.115-15.3
  InterASISDist=DIST(LASI,RASI)
  aa = InterASISDist/2
  mm = $MarkerDiameter/2

                PARAM(MP_LegLength,C,aa,mm)
EndIf

  LATD = 0.1288*MP_LegLength-48.56
  RATD = LATD

  COSBETA = 0.951
  SINBETA = 0.309
  COSTHETA = 0.880
  SINTHETA = 0.476

  COSTHETASINBETA = COSTHETA*SINBETA
  COSTHETACOSBETA = COSTHETA*COSBETA
  Pelvis = [PELF,RASI-LASI,SACR-PELF,xzy]
```

```
LHJC = {C*SINTHETA - aa,C*COSTHETASINBETA - (LATD + mm) * COSBETA,
      -C*COSTHETACOSBETA - (LATD + mm) * SINBETA}*Pelvis

RHJC = {-C*SINTHETA + aa,C*COSTHETASINBETA - (RATD + mm) * COSBETA,
      -C*COSTHETACOSBETA - (RATD + mm) * SINBETA}*Pelvis

OUTPUT(LHJC,RHJC)
{*-----------------------------------------------------------------------------------------------------*}

{*Calculate centre of the head *}

LHead = (LBHD+LFHD)/2
RHead = (RFHD+RBHD)/2
BHead = (LBHD+RBHD)/2
FHead = (LFHD+RFHD)/2

TOPJC = C7+0.125*(FHead-BHead)
OUTPUT(TOPJC)
{*-----------------------------------------------------------------------------------------------------*}
{*Calculating points of interest on the thorax*}

UThorax = (C7+CLAV)/2
LThorax = (T10+STRN)/2
FThorax = (CLAV+STRN)/2
BThorax = (C7+T10)/2

TRX0 = CLAV+0.125*(C7-CLAV)
{*-----------------------------------------------------------------------------------------------------*}
{*Calculating the position of T10*}

MIDJC = T10+0.125*(FThorax-BThorax)
```

```
OUTPUT(MIDJC)

{*----------------------------------------------------------------------------------------------------*}

{*Calculating base of the spine*}

LOWJC = SACR+0.2*(PELF-SACR)

OUTPUT(LOWJC)

{*----------------------------------------------------------------------------------------------------*}

{*Calculating racket centre*}


RACKETCENTRE=(RACKET4+RACKET5+RACKET7+RACKET8)/4

OUTPUT(RACKETCENTRE)


{*=================================================================================
==================*}

{*DEFINING SEGMENTS*}

{*=================================================================================
==================*}


{*PELVIS*}

Pelvis = [PELF,RASI-LASI,SACR-PELF,xzy]

Pelvis = (LHJC+RHJC)/2 + Attitude(Pelvis)

DisplayAxes(Pelvis)


{*FEMURA*}

LFemur = [LKNE,LHJC-LKNE,LKNEL-LKNE,zyx]

RFemur = [RKNE,RHJC-RKNE,RKNE-RKNEL,zyx]

DisplayAxes(LFemur)

DisplayAxes(RFemur)


{*TIBIAE*}

LTibia = [LANK,LKNE-LANK,LANKL-LANK,zyx]

RTibia = [RANK,RKNE-RANK,RANK-RANKL,zyx]

DisplayAxes(LTibia)
```

```
DisplayAxes(RTibia)


{*FEET*}
LFoot = [LMPTM,LANKM-LMPTM,LMPTL-LMPTM,zyx]
RFoot = [RMPTM,RANKM-RMPTM,RMPTM-RMPTL,zyx]
DisplayAxes(LFoot)
DisplayAxes(RFoot)


{*TOES*}
LToes = [LTOE,LMPTM-LTOE,LMPTL-LMPTM,zyx]
RToes = [RTOE,RMPTM-RTOE,RMPTM-RMPTL,zyx]


If $Static == 1 Then
            If $StaticFootFlat = 1 Then
             LRF = {1(LANKM),2(LANKM),3(LMPTM)}
             RRF = {1(RANKM),2(RANKM),3(RMPTM)}
             LFootRef = [LMPTM,LRF-LMPTM,LMPTL-LMPTM,zyx]
             RFootRef = [RMPTM,RRF-RMPTM,RMPTM-RMPTL,zyx]
            EndIf


            MP_LToeFlexOS = 1(<LFootRef,LToes,xyz>)
            MP_RToeFlexOS = 1(<RFootRef,RToes,xyz>)
            PARAM(MP_LToeFlexOS,MP_RToeFlexOS)
EndIf


LToes = ROT(LToes,1(LToes),MP_LToeFlexOS)
RToes = ROT(RToes,1(RToes),MP_RToeFlexOS)


DisplayAxes(LToes)
DisplayAxes(RToes)
```

```
{*HEAD*}
Head = [TOPJC,RHead-LHead,BHead-FHead,xzy]
If $Static == 1 Then
        {*Define HeadRef to have y axis parallel to ground*}
        HeadRef = [TOPJC,RHead-LHead,3(Global),xyz]

        If $StaticHeadLevel = 1 Then
         MP_HeadFlexOS = 1(<HeadRef,Head,xyz>)
        Else
         MP_HeadFlexOS = 0
        EndIf

        PARAM(MP_HeadFlexOS)
EndIf

Head = ROT(Head,1(Head),MP_HeadFlexOS)
DisplayAxes(Head)

{*THORAX*}
{*==============*}
Thorax = [TRX0,UThorax-LThorax,FThorax-BThorax,zxy]
DisplayAxes(Thorax)

{* THORACIC SPINE *}
{*====================*}
upper_back_spine=[MIDJC,C7-LUM1,FThorax-BThorax,zxy]
DisplayAxes(upper_back_spine)

{* LUMBAR SPINE*}
{*==================*}
lower_back_spine=[LOWJC,LUM1-SACR,STRN-LUM1,zxy]
```

```
DisplayAxes(lower_back_spine)


{*HUMERUS*}
{*================*}
LHumerus = [LELB,LSHO-LELB,LELBL-LELB,zyx]
RHumerus = [RELB,RSHO-RELB,RELB-RELBL,zyx]
DisplayAxes(LHumerus)
DisplayAxes(RHumerus)


{*RADIUS & ULNAR*}
{*===========================*}
LRadius = [LWRI,LELB-LWRI,LWRA-LWRI,zyx]
RRadius = [RWRI,RELB-RWRI,RWRI-RWRA,zyx]
DisplayAxes(LRadius)
DisplayAxes(RRadius)


{*HANDS*}
{*=============*}


LHands = [LHAND,LWRI-LHAND,LWRA-LWRI,zyx]
RHands = [RHAND,RWRI-RHAND,RWRI-RWRA,zyx]


If $Static == 1 Then
		If $StaticWristStraight == 1 Then


		MP_LWristFlexOS = 1(<LRadius,LHands,xyz>)
		MP_RWristFlexOS = 1(<RRadius,RHands,xyz>)
		PARAM(MP_LWristFlexOS,MP_RWristFlexOS)


		EndIf
EndIf
```

```
LHands = ROT(LHands,LHands(1),MP_LWristFlexOS)

RHands = ROT(RHands,RHands(1),MP_RWristFlexOS)

DisplayAxes(LHands)

DisplayAxes(RHands)


{*RACKET*}

{*======*}


RACKETFALSE=(RACKET4+RACKET8)/2


{*MAKE SURE RACKET IS LABELLED CORRECT: INSIDE MARKERS SHOULD BE SAME NUMBERS AT BALL IMPACT*}


RacketHead=[RACKETCENTRE,RACKETFALSE-RACKETCENTRE,RACKETFALSE-RACKET4,zyx]


RacketHead=RACKETCENTRE+Attitude(RacketHead)

DisplayAxes(RacketHead)


{*===================================================================================================*}

{*CALCULATE COM POSITIONS OF EACH SEGMENT*}

{*===================================================================================================*}


{*Move location of segment definitions to enable output from Fred's model to be used more easily*}

{*============================================================================================*}


{*Origin of each segment's coordinate system is moved to the proximal end of the segment*}


LFemurFred = LHJC + Attitude(LFemur)

RFemurFred=RHJC + Attitude(RFemur)
```

LTibiaFred=LKNE + Attitude(LTibia)

RTibiaFred=RKNE + Attitude(RTibia)

LFootFred=LANK + Attitude(LFoot)

RFootFred=RANK + Attitude(RFoot)

LToesFred=LMTP + Attitude(LToes)

RToesFred=RMTP + Attitude(RToes)

LHumerusFred=LSHO + Attitude(LHumerus)

RHumerusFred=RSHO + Attitude(RHumerus)

LRadiusFred=LELB + Attitude(LRadius)

RRadiusFred=RELB + Attitude(RRadius)

LHandFred=LWRI + Attitude(LHands)

RHandFred=RWRI + Attitude(RHands)

HeadFred = TOPJC + Attitude(Head)

PelvisFred= Pelvis

ThoraxFred = lower_back_spine

ChestFred = upper_back_spine

{*Output the COM positions*}

LFemurCOM = $LFemurMassLoc*LFemurFred

RFemurCOM = $RFemurMassLoc*RFemurFred

LTibiaCOM = $LTibiaMassLoc*LTibiaFred

RTibiaCOM = $RTibiaMassLoc*RTibiaFred

LHumerusCOM = $LHumerusMassLoc*LHumerusFred

RHumerusCOM = $RHumerusMassLoc*RHumerusFred

LRadiusCOM = $LRadiusMassLoc*LRadiusFred

RRadiusCOM = $RRadiusMassLoc*RRadiusFred

LHandCOM = $LHandMassLoc*LHandFred

RHandCOM = $RHandMassLoc*RHandFred

HeadCOM = $HeadMassLoc*HeadFred

PelvisCOM = $PelvisMassLoc*PelvisFred

ThoraxCOM = $ThoraxMassLoc*ThoraxFred

ChestCOM = $ChestMassLoc*ChestFred

LFootCOM = $LFootMassLoc*LFootFred

RFootCOM = $RFootMassLoc*RFootFred

LToesCOM = $LToesMassLoc*LToesFred

RToesCOM = $RToesMassLoc*RToesFred

OUTPUT(LFemurCOM,RFemurCOM,LTibiaCOM,RTibiaCOM,LFootCOM,RFootCOM,LToesCOM,RToesCOM)

OUTPUT(LHumerusCOM,RHumerusCOM,LRadiusCOM,RRadiusCOM,LHandCOM,RHandCOM)

OUTPUT(HeadCOM,PelvisCOM,ThoraxCOM,ChestCOM)

{*Centre of mass location*}

```
COM_BODY_temp =
(($LFemurMass*LFemurCOM)+($RFemurMass*RFemurCOM)+($LTibiaMass*LTibiaCOM)+($RTibiaMas
s*RTibiaCOM)+($LHumerusMass*LHumerusCOM)+($RHumerusMass*RHumerusCOM)+($LRadiusMas
s*LRadiusCOM)+($RRadiusMass*RRadiusCOM)+($LHandMass*LHandCOM)+($RHandMass*RHandCO
M))

COM_BODY_temp = COM_BODY_temp +
($HeadMass*HeadCOM)+($PelvisMass*PelvisCOM)+($ThoraxMass*ThoraxCOM)+($ChestMass*Chest
COM)+($LFootMass*LFootCOM)+($RFootMass*RFootCOM)+($LToesMass*LToesCOM)+($RToesMass*
RToesCOM)

TOTAL_MASS = $LFemurMass + $RFemurMass + $LTibiaMass + $RTibiaMass + $LHumerusMass +
$RHumerusMass + $LRadiusMass + $RRadiusMass + $LHandMass + $RHandMass + $HeadMass +
$PelvisMass + $ThoraxMass + $ChestMass + $LFootMass + $RFootMass + $LToesMass + $RToesMass

COM_BODY = COM_BODY_temp / TOTAL_MASS


OUTPUT(COM_BODY)


{*================================================================================
==================*}

{*CALCULATE JOINT ANGLES*}

{*================================================================================
==================*}


{*SPINE ANGLES*}


{*Neck Angle*}

NeckAngles = -<Thorax,Head,xyz>(-3)

NeckAngles = <180+NeckAngles(1),NeckAngles(2),NeckAngles(3)>

OUTPUT(NeckAngles)


{*Overall back: Pelvis to Thorax*}

OverallBackAngles = -<Pelvis,Thorax,xyz>(-3)

OverallBackAngles = <180+OverallBackAngles(1),OverallBackAngles(2),OverallBackAngles(3)>

OUTPUT(OverallBackAngles)


{*Cervical Spine:  upper_back_spine >> Head*}
```

```
CervicalAngles = -<upper_back_spine,Head,xyz>(-3)
CervicalAngles = <180+CervicalAngles(1),CervicalAngles(2),CervicalAngles(3)>

{*Thoracic Spine:  lower_back_spine >> upper_back_spine*}
ThoracicAngles = -<lower_back_spine,upper_back_spine,xyz>(-3)
ThoracicAngles = <180+ThoracicAngles(1),ThoracicAngles(2),ThoracicAngles(3)>

{*Lumbar Spine: Pelvis >> lower_back_spine*}
LumbarAngles = -<Pelvis,lower_back_spine,xyz>(-3)
LumbarAngles = <180+LumbarAngles(1),LumbarAngles(2),LumbarAngles(3)>

OUTPUT(LumbarAngles,ThoracicAngles,CervicalAngles)

{*Lumbar on pelvis: Ranson 2009; used in cricket*}

lumbar_cord=[LUM1,t10-LUM1,STRN-LUM1,zxy]
lop=-<Pelvis,lumbar_cord,xyz>
output(lop)
{*------------------------------------------------------------------------------*}
{*SHOULDERS*}
LShoulderAngles = -<Thorax,LHumerus,yxz>
RShoulderAngles = <Thorax,RHumerus,yxz>(-1)
OUTPUT(LShoulderAngles,RShoulderAngles)
{*------------------------------------------------------------------------------*}
{*ELBOWS*}
LElbowAngles = -<LHumerus,LRadius,xyz>(-1)
LElbowAngles = <180+1(LElbowAngles),2(LElbowAngles),3(LElbowAngles)>
RElbowAngles = <RHumerus,RRadius,xyz>
RElbowAngles = <180+1(RElbowAngles),2(RElbowAngles),3(RElbowAngles)>
OUTPUT(LElbowAngles,RElbowAngles)
{*------------------------------------------------------------------------------*}
```

```
{*WRISTS*}

LWristAngles = -<LRadius,LHands,xyz>(-1)

LWristAngles = <180+1(LWristAngles),2(LWristAngles),3(LWristAngles)>

RWristAngles = <RRadius,RHands,xyz>

RWristAngles = <180+1(RWristAngles),2(RWristAngles),3(RWristAngles)>

OUTPUT(LWristAngles,RWristAngles)

{*-----------------------------------------------------------------------------*}

{*KNEES*}

LKneeAngles = -<LFemur,LTibia,xyz>

LKneeAngles = <180+LKneeAngles(1),LKneeAngles(2),LKneeAngles(3)>

RKneeAngles = <RFemur,RTibia,xyz>(-1)

RKneeAngles = <180+RKneeAngles(1),RKneeAngles(2),RKneeAngles(3)>

OUTPUT(LKneeAngles,RKneeAngles)

{*-----------------------------------------------------------------------------*}

{*ANKLES*}

LAnkleAngles = -<LTibia,LFoot,xyz>(-1)

LAnkleAngles = <180+1(LAnkleAngles),2(LAnkleAngles),3(LAnkleAngles)>

RAnkleAngles = <RTibia,RFoot,xyz>

RAnkleAngles = <180+1(RAnkleAngles),2(RAnkleAngles),3(RAnkleAngles)>

OUTPUT(LAnkleAngles,RAnkleAngles)

{*-----------------------------------------------------------------------------*}

{*MTP*}

LMTPAngles = -<LFoot,LToes,xyz>

LMTPAngles = <180+1(LMTPAngles),2(LMTPAngles),3(LMTPAngles)>

RMTPAngles = <RFoot,RToes,xyz>(-1)

RMTPAngles = <180+1(RMTPAngles),2(RMTPAngles),3(RMTPAngles)>

OUTPUT(LMTPAngles,RMTPAngles)

{*-----------------------------------------------------------------------------*}

{*HIPS*}

LHipAngles = -<Pelvis,LFemur,xyz>(-1)

LHipAngles=<180+1(LHipAngles),2(LHipAngles),3(LHipAngles)>
```

```
RHipAngles = <Pelvis,RFemur,xyz>

RHipAngles=<180+1(RHipAngles),2(RHipAngles),3(RHipAngles)>

OUTPUT(LHipAngles,RHipAngles)

{*-----------------------------------------------------------------------------*}


{*=============================================================================
==================*}

{*CALCULATE PROJECTION ANGLES*}

{*=============================================================================
==================*}


{*SHOULDER PROJECTION*}

RSHO_floor = {RSHO(1),RSHO(2),0}

LSHO_floor = {LSHO(1),LSHO(2),0}

shoulder_floor = [(RSHO_floor+LSHO_floor)/2,RSHO_floor - (RSHO_floor+LSHO_floor)/2, {0,0,1},xyz]


Shoulder_Projection_Angle = <global,shoulder_floor,xyz>

Shoulder_Projection_Angle = <Shoulder_Projection_Angle(1),Shoulder_Projection_Angle(2),270-
Shoulder_Projection_Angle(3)>

output(Shoulder_Projection_Angle)

{*-----------------------------------------------------------------------------*}

{*PELVIS PROJECTION*}

RHJC_floor = {RHJC(1),RHJC(2),0}

LHJC_floor = {LHJC(1),LHJC(2),0}

pelvis_floor = [(RHJC_floor+LHJC_floor)/2,RHJC_floor - (RHJC_floor+LHJC_floor)/2, {0,0,1},xyz]

Pelvis_Projection_Angle = <global,pelvis_floor,xyz>

Pelvis_Projection_Angle = <Pelvis_Projection_Angle(1),Pelvis_Projection_Angle(2),270-
Pelvis_Projection_Angle(3)>

output(Pelvis_Projection_Angle)


{*-----------------------------------------------------------------------------*}
```

```
{*====================================================================================
==================*}

{*CALCULATE RACKET ANGLES*}

{*====================================================================================
==================*}


          RacketGlobalAngles = <Global,RacketHead,xyz>2

          RacketGlobalAngles =
<1(RacketGlobalAngles),2(RacketGlobalAngles),3(RacketGlobalAngles)>

          RacketAnglesRadius = <RRadius,Rackethead,xyz>

          RacketAnglesRadius =
<1(RacketAnglesRadius),2(RacketAnglesRadius),3(RacketAnglesRadius)>

          RacketAnglesHand = <RHands,Rackethead,xyz>

          RacketAnglesHand =
<1(RacketAnglesHand),2(RacketAnglesHand),3(RacketAnglesHand)>


OUTPUT(RacketAnglesHand,RacketAnglesRadius,RacketGlobalAngles)
```