# Cardiff School of Sport

**DISSERTATION ASSESSMENT PROFORMA:**

**Empirical**

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<td>The Impact of Ground Reaction Force and Joint Kinematics on the Tennis Serve of Collegiate Players</td>
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**Comments**

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<th><strong>Section</strong></th>
<th><strong>Introduction and literature review</strong></th>
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<th><strong>Section</strong></th>
<th><strong>Methods and Research Design</strong></th>
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The Impact of Ground Reaction Force and Joint Kinematics on the Tennis Serve of Collegiate Players

(Dissertation submitted under the discipline of Biomechanics)

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ACKNOWLEDGEMENTS</strong></td>
<td>i</td>
</tr>
<tr>
<td><strong>ABSTRACT</strong></td>
<td>ii</td>
</tr>
<tr>
<td><strong>CHAPTER ONE</strong></td>
<td></td>
</tr>
<tr>
<td><strong>REVIEW OF LITERATURE</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Service Technique</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Overarm Throwing</td>
<td>3</td>
</tr>
<tr>
<td>1.4 The Kinetic Chain</td>
<td>4</td>
</tr>
<tr>
<td>1.5 Leg Drive</td>
<td>5</td>
</tr>
<tr>
<td>1.6 Trunk and Upper Extremity</td>
<td>8</td>
</tr>
<tr>
<td><strong>CHAPTER TWO</strong></td>
<td></td>
</tr>
<tr>
<td><strong>METHODOLOGY</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 Research Design</td>
<td>12</td>
</tr>
<tr>
<td>2.2 Pilot Studies</td>
<td>12</td>
</tr>
<tr>
<td>2.3 Sample</td>
<td>12</td>
</tr>
<tr>
<td>2.4 Data Collection</td>
<td>13</td>
</tr>
<tr>
<td>2.41 Data Collection</td>
<td>13</td>
</tr>
<tr>
<td>2.42 Filming</td>
<td>13</td>
</tr>
<tr>
<td>2.43 Force Plates</td>
<td>15</td>
</tr>
<tr>
<td>2.5 Data Processing</td>
<td>15</td>
</tr>
<tr>
<td>2.51 Digitising</td>
<td>15</td>
</tr>
<tr>
<td>2.52 Reconstruction</td>
<td>16</td>
</tr>
<tr>
<td>2.6 Data Reduction</td>
<td>17</td>
</tr>
<tr>
<td>2.61 Data Smoothing</td>
<td>17</td>
</tr>
<tr>
<td>2.7 Data Analysis</td>
<td>18</td>
</tr>
<tr>
<td>2.8 Reliability</td>
<td>19</td>
</tr>
<tr>
<td>2.9 Accuracy</td>
<td>19</td>
</tr>
<tr>
<td>2.10 Statistical Analysis</td>
<td>19</td>
</tr>
</tbody>
</table>
CHAPTER THREE

RESULTS

CHAPTER FOUR

DISCUSSION
4.1 Leg Drive 28
4.2 Backswing 30
4.3 Acceleration Phase 31
4.4 Impact 33
4.5 Limitations 35
4.6 Future Research 36
4.7 Conclusion 37

REFERENCE LIST

APPENDICIES
Appendix A - Informed Consent Form A1
Appendix B - Participant Information Sheet B1
### LIST OF TABLES

**Table 1.** Root mean squared difference (RMSD) %  
22

**Table 2.** Root mean squared difference (RMSD) %  
22

**Table 3.** Kinematic characteristics of the foot-up and foot-back serve techniques  
22

**Table 4.** Characteristics of the FU and FB serve technique  
23

**Table 5.** Kinematics of the backswing  
23

**Table 6.** Vertical velocities of the hip, shoulder and end of racket when hip was at maximum vertical velocity (m/s)  
24

**Table 7.** Maximum resultant linear velocities of segments and racket end points prior to impact (m/s)  
24

**Table 8.** Resultant linear velocities of segments and racket end points at impact (m/s)  
25

**Table 9.** Ball movement prior to impact  
25

**Table 10.** Three-dimensional angles of the racket side of body at impact (°)  
25

**Table 11.** Ball Movement at impact  
25
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.</td>
<td>Graphic representation of the functional kinetic chain of the tennis serve demonstrating body segment velocities as a function of time.</td>
<td>5</td>
</tr>
<tr>
<td>Figure 2.a.</td>
<td>Filming setup.</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.b.</td>
<td>Camera placement.</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3.</td>
<td>Anatomical landmarks.</td>
<td>16</td>
</tr>
<tr>
<td>Figure 4.</td>
<td>The ankle, knee, hip, shoulder, elbow and wrist joint angles defined.</td>
<td>18</td>
</tr>
<tr>
<td>Figure 5.</td>
<td>Resultant linear velocities of the hip, shoulder, elbow, wrist and racket after leg drive initiation for the highest ranked player.</td>
<td>26</td>
</tr>
</tbody>
</table>
Acknowledgements

Firstly I would like to thank the eight participants who took part in this study, their engagement and cooperation made the study possible. I wish to thank my dissertation supervisor Ian Bezodis for his patience and constant support throughout the year. The input he provided always guided me in the right direction and for that I am grateful. Finally the assistance of the biomechanics technicians, Michelle, Mel and Joe, during testing was invaluable and greatly appreciated.
Abstract

**Purpose:** The serve plays a key role in determining the outcome of a match but its complexity means it is one of the most difficult shots in tennis. Due to the paucity of research involving the interaction of the leg drive and upper limbs in the tennis serve, the aim of the current study was to examine how ground reaction force and joint kinematics influence service motion in collegiate players. **Methods:** Three-dimensional data was reconstructed using the direct linear transformation (DLT) method. Three flat serves of eight collegiate male players were recorded from two laterally placed cameras operating at 50 Hz. Ground reaction force (GRF) data was collected using a Kistler 5233A force plate operating at 1000 Hz. Group means and standard deviations were reported for each of the parameters measured. **Results:** An effective leg drive consisting in peak front and rear knee flexion angles of 69.2° and 78.5° respectively assisted in generating a ground reaction force (GRF) of 2.26 BW. As the shoulder was driven vertically at a maximum velocity of 2.68 m/s, the racket was positioned down behind the back with a velocity of -5.23 m/s. An efficient proximal to distal sequencing culminated at the wrist producing a mean resultant racket head velocity of 31.06 m/s and a subsequent resultant ball velocity of 36.14 m/s. **Discussion and conclusion:** The leg drive has a dual role of initiating the kinetic chain and preparing the racket for the forward swing. By better coinciding the time of maximum vertical hip velocity with the racket's maximum downward velocity, the racket can accelerate over a greater distance to impact. While service speeds were lacking compared to other collegiate performers in previous studies, an effective leg drive and functional kinetic chain provide a solid foundation for the serve to be developed in training.
CHAPTER ONE
LITERATURE REVIEW
Review of Literature

1.1 Introduction

The serve is the first shot played in tennis, it initiates a point and therefore is the only shot the player has full control over. A player can choose the direction, speed and spin of the ball without the opponent directly influencing his or her decision, giving the server an immediate advantage. However with the serve solely dependent on the player, it can become a disadvantage if the player possesses a weak technique given that technique has been identified as most crucial element to performance (de Subijana and Navarro, 2009). A good first serve has the potential to directly win the point through an ace or winning serve or indirectly by forcing a weak return from the opponent; setting up an easy second shot (Gillet et al. 2009). A poor first serve or a second serve allows more opportunity for the opponent to take control of the point, giving away that advantage. At an elite level, where difference in skill level is minimal, the player serving has a higher chance of winning that game than the player returning and so the effectiveness of a tennis serve is crucial to the outcome of the match. For these reasons the first serve has often been described as the most crucial shot in tennis (Reid et al. 2010).

Service speeds have increased due to technology developments and demands of the game with Ivo Karlovic reaching speeds up to 69 m/s (ATP World Tour Records, 2011). The average ball speeds for female and male players however has been reported as 34.4 m/s and 42.2 m/s respectively (Elliott, Marsh and Blanksby, 1986). Furlong (1995) established that the serve is more essential in men’s tennis than in women’s. This could be contributed to the fact men hit the ball at a higher velocity (O’Donoghue and Ingram, 2001) and are more attacking on the return and so a good serve is required. It is widely accepted that increased service speeds when paired with a high first serve percentage will increase the chances of winning (Brody, 2003). Furthermore when ball speeds over 44 m/s are reached, the player returning has been proved to make errors (Haake Rose and Kotze, 2000). This provides a great incentive for players and coaches to develop this part of their game. A technical and biomechanical understanding of what constitutes an effective serve is important for success.
1.2 Service Technique

The tennis serve is a closed skill and so the consistency to which the skill can be implemented or ‘form’ of performance should be the focus over the ball velocity and direction (Gentile, 1972). To improve skill level it was therefore suggested that providing feedback on information regarding movement patterning would be appropriate for skill development (Rikli and Smith, 1980). It is logical to assume that biomechanical analysis of the key elements of service motion will naturally encourage a greater understanding by a coach or player to identify strengths and weaknesses to concentrate on in training.

1.3 Overarm Throwing

Coaches often liken overarm throwing to that of a tennis serve and is regularly used to enhance understanding when developing basic technique with novices. Perlstein (1993) described the hitting motion as ‘throwing the racket up and out’ (p.62). Indeed when looking at a baseball pitch, javelin throw, American football pass and tennis serve there have been similarities identified in the upper limb movements between the different sports (Fliesig, 1996). In particular Cooper and Glasgow (1976) found that rotation of the shoulder was one of the primary contributors to the end product in all of the above and also a badminton smash, highlighting the likeness of their characteristics. Adrian and Enberg (1971) however identified significant differences in the activity of the segments and questioned whether such a broad range of overarm activities, such as the above, could really be defined equally. Upon further investigation Anderson (1979), who also found irregularities in the spatial-temporal characteristics of certain muscles between the overarm throw and tennis serve, revealed this was due to the weight and size of the object being ‘thrown’; a tennis racket is considerably larger and holds more mass than that of a baseball or football.
1.4 The Kinetic Chain

In overarm throwing (striking) the main aim is to project an object with velocity and accuracy (Van den Tillaar and Ettema, 2003). To perform such complex movements requires a smooth and efficient technique that will maximise performance whilst reducing the likelihood of injury (Elliott, 2006). By coordinating individual body segments so that joint centre velocities progressively attain their maximum in a proximal to distal sequence (Liu, Leigh and Yu, 2010), athletes can enhance the speed of release at the distal segment. This ‘kinetic chain’ has been studied in many sports such as baseball (Feltner, 1989), javelin throwing (Lui et al., 2010), the tennis forehand (Bahamonde and Knudson, 2003), the golf swing (Nesbit, 2005) and ball striking in football (Shan and Westerhoff, 2005) and is considered a key determinant of success in overarm throwing events (Bartlett, Mueller, Lindinger, Brunner, and Morriss, 1996). It is not surprising therefore that the speed of the racket upon impact has been described as crucial in generating ball speed (Elliott, Mester, Kleinoder, and Yue, 2003) and so the effectiveness of a tennis serve can be attributed to a player’s ability to develop this.

The biomechanical factors affecting racket head speed in the tennis serve have been reported in a number of studies (Bahamonde, 2000; Sprigings, Marshall, Elliott and Jennings, 1994; Durovic, Lozovina, Pavicic and Mrduljas, 2008). Quantifying the velocities of body segments, the angle of joints and ball speeds allowed a kinetic chain to be defined in the tennis serve also. High end point racket speed requires a number of body segments to move in a sequenced proximal to distal fashion (Elliott, 2003). This type of multi-segment coordination has been shown to involve linear and angular changes in velocity of adjoining links creating a transfer of kinetic energy (de Subijana and Navarro, 2009). Force generation via a leg drive initiatives movement up through the trunk and upper extremity culminating at the wrist producing high end point velocity (racket head speed).

Although Girard, Micallef and Millet (2005) characterised the kinetic chain as having the velocities of body segments increasing in a linear proximal to distal sequence (Figure 1), Sciacca and Kibler (2006) highlighted that the tennis serve
does not solely involve a progressively linear pattern from one segment to the next segment. The authors reported how maximum elbow velocity is in fact attained prior to maximum shoulder velocity. Nevertheless, with the velocity of each segment dependant on the movement and orientation of the previous, any alteration in the link will result in a loss of energy and most likely impact negatively on the outcome at the distal end.

![Figure 1](image.png)

Figure 1. Graphic representation of the functional kinetic chain of the tennis serve demonstrating body segment velocities as a function of time. Adapted from Abrams, Sheets, Andriacchi and Safron (2011).

### 1.5 Leg Drive

Previously labelled as the origin of the tennis serves kinetic chain (Reid, Elliott and Alderson, 2008), the leg drive has been identified as one of the biggest contributors to racket head speed (Bahamonde and Knudson, 2003; de Subijana and Navarro, 2009). Knee flexion provides the starting point when developing angular and linear momentum through ground reactions forces (GRF) (Girard, Micallef and Millet, 2007). Putnam (1993) ‘summation of speed’ principle indicates how force developed by the distal segments is dependant of the interaction with the proximal segment’s velocity therefore highlighting the role the lower extremity
plays in the serve. With efficient upper extremity coordination dependant on the lower extremity movement, it could also be expected if the proximal segments activity is increased i.e. higher GRF, then a greater energy will be transferred through the kinetic chain resulting in an enhanced distal segment function.

While the influence of the leg drive on serve effectiveness remained relatively unknown in comparison to the upper extremity (Girard, Micallef and Millet, 2005), the function of lower limb segments has been brought much more into focus in recent years (Girard et al., 2007; Girard, Micallef and Millet, 2005; Sweeney, Reid and Elliot, 2012; Reid, Elliott and Alderson, 2008). Just how crucial the lower limbs are to serve efficiency was demonstrated when Girard et al. (2007) investigated the influence of restricting knee motion during the first serve. By preventing the fluent motion required for an effective serve (Elliott, 2006); it was revealed that lower ground reaction forces (GRF) were produced and resultant ball speeds were reduced by approximately 7 m/s. Players of an intermediate playing standard generated a GRF of 1.91 BW with knee flexion but this reduced to 1.36 BW when knee flexion was restricted. In an attempt to compensate for the loss of force from the proximal segments the dysfunctional kinetic chain will increase the contribution further on in the chain in what Kibler (2009) referred to as ‘playing catch-up’. This was made evident in a study conducted by Elliott et al. (2003) in which a decreased knee extension loaded the shoulder and elbow with greater torques, naturally increasing the potential for injury as well as inhibiting shoulder rotation; a key element in serve effectiveness (Elliott and Alderson, 2003).

A few studies have attempted to classify the most effective leg drive through the amount of knee flexion a player experiences. Lo et al. (2004) reported a mean maximum knee bend of 30° for a flat serve in elite players. This was greater than the 0 - 10° which Elliott et al. (2003) described as ineffective however much lower than the recommendations of 70° ± 10° presented by Elliott (2006). A possible reason for such a low level of knee flexion could be attributed to methodological issues. GRF was collected using two force plates; each participant was required to keep one foot on one force plate and the other foot on another. Firstly, for players to keep their back foot in relatively the same position they must have to adopt the foot back (FB) stance, a technique which has been associated with greater knee
flexion (Reid et al., 2008) (for more detail see Stance section). Secondly, it is highly unlikely that both force plates were positioned in a way that suited individual participant lower limb movement. Perhaps wary to keep both feet in the confined area, natural flexion and extension may not have occurred, altering their natural service motion. Previously witnessed peak knee flexion angles of 69.9° - 85.7° (Reid et al., 2008) and 57.3° (Elliott et al., 1986) certainly support this; it would seem unlikely that a knee bend of 30° could generate an effective serve.

While peak knee flexion is not a key determinant of success, a greater range of front and rear knee extension has the ability to increase the range of movement the racket takes behind the players back and put the muscles on pre-stretch (Bahamonde, 1997). This in turn will increase the path of the racket and therefore allows for greater racket head velocity (Elliott and Marsh and Blanksby, 1986). This point was further reinforced by Elliott (2006) who established maximal service power can only be generated with efficient timing of the leg drive and racket preparation. The role of the lower extremity in providing the foundations for the transfer of energy and momentum was further emphasised when Kibler (2009) reported how the legs along with the trunk accounted for 51 per cent of the kinetic energy and 54 per cent of the force developed by the top players. It would seem unwise then to conduct research involving the upper extremity in a tennis serve without an appreciation of the lower limb influence.
1.5.1 Stance

Variation in leg drive can be partly attributed to a player’s stance during the service motion (Elliott, 2001). The foot up (FU) technique requires the player to bring their back foot forward allowing for more forceful movement, a factor which Elliott (2001) explained lends itself more naturally to an ‘up and out’ service action. The foot back (FB) technique results in the player maintaining their back foot in its original position. This wider base allows for increased squat depth, producing larger extension of the knee joint (Reid et al., 2008). Furthermore, this stance creates a larger propulsive force forward with the back leg enabling the player to move to the net quicker (Girard et al., 2007). Although the FU technique has been shown to produce a greater vertical force and vertical displacement (Bahamonde and Knudson, 2001), there is in fact no difference in the outcome service velocities between the two stances (Elliott and Wood, 1983), thus suggesting that foot position ultimately is a matter of personal choice providing the ‘leg drive’ is done effectively.

1.6 Trunk and Upper extremity

While the leg drive provides the foundations for the serve, high ball speeds can only occur if energy and momentum is transferred appropriately through the upper body to the distal segment (racket). With this in mind, it is easy to understand why Correia and Veloso (1998) labelled the trunk as the fundamental link in the kinetic chain given that it connects these two extremities. The importance of trunk rotation had been previously identified through the changes of angular momentum throughout the serve (Bahamonde, 2000) however Sweeny, Reid and Elliott (2012) more specially investigated the trunk and its role in the tennis serve. They found strong correlations between the leg drive and the vertical drive of the trunk, and vertical drive of the trunk and subsequent racket head velocity. From this it could be expected that the vertical velocity of the shoulder (the top of trunk) would provide significant information on the effectiveness of the leg drive and the potential to produce high racket head speeds.
Different body segments have been shown to have their own individual roles in supporting the service motion (Correla and Veloso, 1998), however their main role as discussed is to work in harmony to generate racket head speed. Previous studies have identified the contribution of different body segments to racket head speed (Elliott et al., 1995; Gordon and Dapena, 2006; Sprigings et al., 1994). A player whose serve was identified to lack speed was analysed by Sprigings et al. (1994) to determine how the rotation of each segment in the upper body contributed to racket head velocity. The authors stated how internal rotation of the shoulder (30 %) and flexion of the hand or wrist (26 %) played the largest role generating racket head speed. Elliott et al. (1995) reported similar contributions from internal rotation of the shoulder (54.2 %) and wrist flexion (31 %) for a group of amateur players. These results should be treated somewhat with caution however given that both studies included pre and post impact data into a smoothing program which was not fully capable of dealing with the sudden decelerations of the racket head (Gordon and Dapena, 2006). Consequently the peak magnitude of the deceleration is lessened and the contributions to racket head velocity will not be a true reflection of the real values. Nevertheless it is apparent from those findings that the shoulder has a crucial role in developing racket head speed irrespective of standard. Such was its importance that Durovic, Lozovina and Mrduljas (2008) used specific movements of the shoulder to define and create a new biomechanical model based on the performance of 70 elite Association of Tennis Professional (ATP) ranked players.

With such large contributions to racket head speed coming from the upper arm it is unsurprising that injuries at the shoulder (Van der Hoeven and Kibler, 2006), elbow (Hammer, Rupp, Ensslin, Kohn, and Seil, 2000), wrist and hand (Rettig, 1994) are a common occurrence among tennis players. It is for this reason also that the interaction of adjoining segments is of great interest to researchers especially in non-elite performers who may not possess the most efficient technique.

Girard et al., (2007) highlighted the need for further research into the link between lower limb motion and racket kinematics when looking at serve effectiveness. Furthermore much of the previous literature (Bahamonde, 2000; de Subijana and
Navarro, 2009; Đurović, et al., 2008) has predominantly used elite performers. The majority of studies looking at non-elite performers (Elliott et al., 1995) orientated their research around either the upper extremity or lower extremity function and failed to consider them collectively. Fleisig, Nicholls, Elliott and Escamilla (2003) concluded their work on Olympic athletes emphasising the importance for future research into the players of varying abilities to gain knowledge on how associations between service kinetics, serve kinematics and ball speed differ at these levels. Understanding the role of joint motions and ground reaction force for collegiate athletes in achieving appropriate sequencing of body segments will give a better insight into the mechanics of the tennis serve at an intermediate level. This information can then be used to compare against a model of good practice i.e. elite performers which may aid progression through appropriate technical training. Therefore the purpose of the study was to analyse how ground reaction force and joint kinematics influence on the performance of the tennis serve in collegiate players.
CHAPTER TWO
METHODOLOGY
Methodology

2.1 Research Design

The current study involved descriptive research, which implemented three-dimensional (3D) analysis with an aim to describe the causes of motion in a 3D space (Gordon, Robertson, Caldwell, Hamill, Kamen and Whittlesey, 2004). Direct linear transformation was used to generate 3D spatial coordinates; this method produces an accurate reconstruction of human movement. The study was conducted in agreement with British Association of Sport and Exercise Sciences (BASES) standards.

2.2 Pilot Studies

A pilot study was conducted two weeks prior to testing to allow the tester to become accustomed with the equipment and to inform the protocol for subject testing. Appropriate camera placement, frame rate and shutter speed were trialled and practised with a decision being made on each of these as the pilot session ended.

2.3 Sample

Eight male collegiate tennis players undertook testing. Mean (± SD) age, height and body mass of the participants were 20.88 (± 0.64) years, 1.79 (± 0.05) m and 72.72 (± 6.47) kg respectively. All participants were competing in one of the three Cardiff Metropolitan University teams and have been playing tennis competitively for at least three years as well as holding a Lawn Tennis Association (LTA) national ranking. Each player completed an informed consent form prior to testing; testing itself had been ethically approved by Cardiff Met's Ethics Committee (UEC)
2.4 Data Collection

2.4.1 Protocol

Prior to participant testing, a calibration object was assembled and filmed in the area of service motion to be later used to obtain reconstructions. Each athlete was asked to complete a series of warm up exercises led by themselves in order for them to maximise performance. Each athlete performed the test in shorts and a t-shirt to make it easier to identify the anatomical landmarks in the analysis. Each subject performed the test with the use of their own equipment i.e. tennis racket and shoes to replicate a competitive situation and therefore maximise performance. Once correctly positioned, subjects were asked to perform a series of serves until three successful serves were recorded. A successful serve was one which landed in the target area without the athlete altering their natural service action. The target area was left service box of the tennis court (Figure 2a). Upon completion of three successful serves the following subject repeated this process. This routine continued until all 8 athletes had been tested.

2.4.2 Filming

Two Sony HVR-Z1E (Sony, Japan) digital camcorders operating at 50 Hz were mounted on tripods and used to reconstruct service motion in 3D. The first camera was placed 6.13 m behind the participant and the second camera was placed 5.71 m to the right of the participant. Figure 2b shows the layout of the cameras which gave the most beneficial field of vision of service motion to identify the anatomical landmarks. A convergence angle of 89\(^0\) was selected following a pilot study, this was within the range that was deemed acceptable (60 -120\(^0\)) for Direct Linear Transformation with 90\(^0\) being most suitable (Bartlett, 1997). A shutter speed of 1/600s was selected to provide appropriate lighting and clarity to the image.
Figure 2a. Filming set up (adapted from Bahamonde, 2000)

Figure 2b. Camera Placement
2.4.3 Force plate

A Kistler 5233A (Kistler, Winterthur, Switzerland) force plate embedded into the track sampled at 1000 Hz was used to collect ground reaction force (GRF) data. The force plate provided enough space for subjects to move freely enough that their natural foot placement was maintained. GRF data consisted of mediolateral (Fx), anteroposterior (Fy) and vertical (Fz) components (Figure 2.a) which were saved and processed through Kistler V3.2.6 Bioware software (Kistler, Winterthur, Switzerland) on PC.

2.5 Data Processing

2.5.1 Digitising

Each service motion was manually digitised using Peak Motus 9.0 system (Vicon, Los Angeles, CA). A 17-point spatial model (Figure 3) was used to inform this process. This model included the body landmarks; shoulders, right elbow, right wrist, right hand, hips, knees, ankles and four racket points. Each point was digitised starting a few frames prior to the ball toss, continuing in every frame up until the front foot landed after ball contact. Additional digitising was done to define the calibration object. The calibration object was a pre-calibrated apparatus which covered the area in which the service motion took place and was filmed prior to subject testing.
2.5.2 Reconstruction

To process 2D coordinates into 3D coordinates Direct Linear Transformation (DLT) was employed (Abdel-Aziz and Karara, 1971). An absence of mechanical synchronisation amongst the two cameras meant the ‘instants of exposure’ in one recording was not consistent with the instants of exposure in the other recording (Gordon and Dapena, 2006). Even with synchronous cameras it is necessary to identify a pair of matching video fields or film frames (Yeadon, 1999). This was done with a series of Light Emitting Diodes (LED) which pulsed in view of each camera. By identifying which frame in each the LED configuration occurred, a function of the Peak Motus system allowed each film to be cut to the same length whilst synchronising the frames of each camera. Synchronisation was accurate up to 0.001s.

There are of course errors associated with DLT, whilst some of these can be minimised through a sound experimental procedure, co-ordinates will be contaminated by some systematic and random error (Bartlett, 1997). Sources of
error include image distortion, inaccurate scaling and operator error when identifying body landmarks, synchronisation error, and calibration error.

2.6 Data Reduction

2.6.1 Data Smoothing

It is widely accepted the visual recordings of human movement will lead to noise within the data (Bartlett, 1997). Errors from the digitising process will be amplified during the differentiation process when calculating velocity and acceleration becoming contaminated with high frequency noise (Robertson et al., 2004). These errors are not tolerable and the smaller errors must be eliminated at the displacement stage to validate acceleration data. To remove the noise a low pass digital filter was used. Generally human movement occurs at a low frequency (4 – 8 Hz) (Bartlett, 1997). Therefore current study implemented a cut of frequency of 6 Hz for the coordinates, 3D angles and linear velocities of the ankle, knee, hip, shoulder, elbow and wrist.

Previous studies involving the digitising of impact motion have identified issues with data smoothing (Knudson and Bahamonde, 2001). Upon impact, the data smoothing program is unable to differentiate between rapid deceleration of the racket (acceleration of the ball) and the illegitimate accelerations generated from the noise (Gordon and Dapena, 2006). Subsequent over smoothing paired with the fact that deceleration of the racket will be shown to occur before impact will cause systematic errors around the time of impact. For this reason it was decided the coordinates and linear velocities of the racket and ball were to be omitted from the data smoothing program.
2.7 Data Analysis

For the purpose of the current study the following events were defined through human observation; ball release, the point at which knee extension began and ball contact. The serve was split into two phases; the backswing and forward swing. The back swing was defined as the start of service motion to when the racket reached its lowest point behind the back and the forward swing was defined as from end of the backswing up until ball contact. The kinematic data reported included displacement, 3D angles and linear velocities of the ankle, knee, hip, shoulder, elbow, wrist and the top of the racket, and resultant ball speeds. The 3D joint angles are defined in Figure 4, with peak knee flexion describing the minimum knee angle. Ground reaction force data was collected every 0.001 s. The instants of touchdown and take-off from the force plate were defined as; when the vertical GRF first rose above 10 N (touchdown) and reduced to 10 N (take-off) (Hunter, Marshall and McNair, 2005).

![Figure 4. The ankle, knee, hip, shoulder, elbow and wrist joint angles defined.](image-url)
2.8 Reliability

To determine the reliability of the 3D digitising the trial was digitised twice with a 1 week gap in between each test, eliminating the possibility of the learning effect. Intra-observer reliability was measured using the root mean square difference (RMSD) which highlighted the differences in two sets of reconstruction data.

Digitiser reliability was evaluated at the variables which were of particular relevance throughout the digitising process; right knee angle (º), right knee vertical velocity (m/s), racket end-point resultant velocity (m/s) and resultant ball speed (m/s).

2.9 Accuracy

The accuracy of the digitising process was assessed again using RMSD of two sets of reconstruction data. The dimensions of the racket head and racket neck were of known value which used to compare against dimensions of digitised racket head and neck.

2.10 Statistical Analysis

All descriptive statistics are presented as a mean ± standard deviation, unless otherwise stated. The equations that are used throughout the study are:

Mean:

\[ \bar{x} = \frac{\sum x}{n} \]

Standard deviation:

\[ \sigma = \frac{\sqrt{\sum d^2}}{n} \]
Root Mean Squared Difference (RMSD):

$$RMSD = \sqrt{\frac{\sum_{t=1}^{n}(x_{1,t} - x_{2,t})^2}{n}}$$

RMSD expressed as a percentage:

$$RMSD \% = \frac{RMSD}{x_{\max} - x_{\min}} \times 100$$
CHAPTER THREE
RESULTS
Results

Table 1 shows some systematic bias, a maximum RMSD value of 7.58% when testing the digitiser reliability of right knee linear velocity indicates some residual variance. Table 2 presents RMSD values to test for digitiser accuracy. The racket proportions, which dimensions were known, produced higher levels of residual variance (Racket head = 16.16%; Racket neck = 20.08).

<table>
<thead>
<tr>
<th>Table 1. Root mean squared difference (RMSD) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right knee angle</td>
</tr>
<tr>
<td>Right knee linear velocity</td>
</tr>
<tr>
<td>Resultant ball speed</td>
</tr>
<tr>
<td>Top of racket resultant speed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. Root mean squared difference (RMSD) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racket head</td>
</tr>
<tr>
<td>Racket neck</td>
</tr>
</tbody>
</table>

Of the eight participants, seven adopted a foot-up (FU) stance and only one used the foot-back (FB) technique as described by Elliott and Wood (1983). The foot-back style resulted in the player being further into court with their first step (FB = 0.67 m; FU = 0.62 m) however the FU style caused the players to impact the ball at a greater height in relation their standing height (FU = 142.61%; FB = 138.58%).

<table>
<thead>
<tr>
<th>Table 3. Kinematic characteristics of the foot-up and foot-back serve techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance into court with first step (m)</td>
</tr>
<tr>
<td>Height of front foot off ground at impact (m)</td>
</tr>
<tr>
<td>Impact position relative to standing height (%)</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Total</td>
</tr>
<tr>
<td>FU</td>
</tr>
<tr>
<td>FB</td>
</tr>
</tbody>
</table>
Table 4 shows the further kinematic and kinetic characteristics of the FU and FB stance. Both techniques displayed knee flexion. The FU stance generated greater peak knee flexion angle at the front (+6.16°) and rear knee (+20.35°). The FU technique generated a higher vertical ground reaction force relative to body weight (BW) (FU = 2.26 BW; FB = 2.25 BW), contributing to those participants to contact ball at a greater height (Table 3).

<table>
<thead>
<tr>
<th>Characteristics of the FU and FB serve technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front knee flexion (°)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Total Mean</td>
</tr>
<tr>
<td>SD</td>
</tr>
<tr>
<td>FU Mean</td>
</tr>
<tr>
<td>SD</td>
</tr>
<tr>
<td>FB Mean</td>
</tr>
<tr>
<td>SD</td>
</tr>
</tbody>
</table>

During the back swing (Figure 5) the mean minimum elbow angle reached 50.66° as the racket moves downward behind the back however from this it is evident participants did not complete full flexion of the elbow. As the elbow angle reached 90° the upper arm was abducted producing an average shoulder angle of 79.90°. Meanwhile the knee angle for all participants was averaged at 114.26°; this value was 14.08° form maximum knee flexion.

<table>
<thead>
<tr>
<th>Table 5. Kinematics of the backswing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder angle when elbow 90° (°)</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>SD</td>
</tr>
</tbody>
</table>

Table 6 shows the vertical velocities of the hip, shoulder and the end of the racket when the hip was at maximum vertical velocity. At the time where the trunk begins to drive upwards the racket is positioned behind the back, six of the eight participants produced negative end of racket velocity when the hips vertical
velocity was at a maximum. Six players produced maximum negative racket velocity before their hip was at maximum vertical velocity. The player who was classified to have the best Lawn Tennis Association (LTA) ranking was able to generate an end of racket velocity nearest to its maximum (77% of maximum negative velocity) as the hip was travelling at maximum vertical velocity. The lowest ranked player however recorded 28% of maximum negative end of racket velocity.

Table 6. Vertical velocities of the hip, shoulder and end of racket when hip was at maximum vertical velocity (m/s)

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Hip</th>
<th>Shoulder</th>
<th>End of racket</th>
<th>Maximum negative vertical velocity of end of racket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.31</td>
<td>2.68</td>
<td>-5.23</td>
<td>-10.93</td>
</tr>
<tr>
<td>SD</td>
<td>0.35</td>
<td>0.58</td>
<td>4.92</td>
<td>2.64</td>
</tr>
<tr>
<td>Highest ranked player</td>
<td>Mean</td>
<td>2.77</td>
<td>2.85</td>
<td>-5.32</td>
</tr>
<tr>
<td>SD</td>
<td>0.29</td>
<td>0.64</td>
<td>1.30</td>
<td>0.89</td>
</tr>
<tr>
<td>Lowest ranked player</td>
<td>Mean</td>
<td>1.877</td>
<td>1.91</td>
<td>-2.32</td>
</tr>
<tr>
<td>SD</td>
<td>0.21</td>
<td>0.10</td>
<td>0.06</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 7 presents the maximum resultant velocities of the segments at the knee, hip, shoulder, elbow, and wrist and at the racket end point prior to impact. Each segment achieved its maximum velocity in a proximal to distal sequence with the knee occurring first followed by the other segments in quick succession. The racket reached an average maximum speed of 31.06 m/s 0.02 s before impact and decreased to 30.92 m/s at contact (Table 8). For five of the players however the end point racket velocity was less than maximum at impact.

Table 7. Maximum resultant linear velocities of segments and racket end points prior to impact (m/s)

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Knee</th>
<th>Hip</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Wrist</th>
<th>End of racket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.17</td>
<td>2.66</td>
<td>4.02</td>
<td>7.13</td>
<td>8.85</td>
<td>31.06</td>
</tr>
<tr>
<td>SD</td>
<td>0.27</td>
<td>0.38</td>
<td>0.56</td>
<td>0.54</td>
<td>0.74</td>
<td>2.32</td>
</tr>
<tr>
<td>Time prior to impact (s)</td>
<td>Mean</td>
<td>0.17</td>
<td>0.16</td>
<td>0.12</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>SD</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Table 9 shows the ball characteristics leading up to impact. Ball contact occurred 2.55 m off the ground. A ball toss of 3.19 m meant that the ball dropped 0.65 m resulting in a downward velocity of 3.71 (m/s) prior to contact. The standard deviation value for ball toss height highlights the variation in this parameter and subsequently the ball velocity at impact and ball displacement.

Table 9. Ball movement prior to impact

<table>
<thead>
<tr>
<th></th>
<th>Height of toss (m)</th>
<th>Height of impact (m)</th>
<th>Velocity at impact (m/s)</th>
<th>Distance Dropped (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3.19</td>
<td>2.54</td>
<td>3.71</td>
<td>0.65</td>
</tr>
<tr>
<td>SD</td>
<td>0.35</td>
<td>0.20</td>
<td>1.01</td>
<td>0.34</td>
</tr>
</tbody>
</table>

A relatively extended body (Table 10), made evident through the knee, hip and elbow angle at contact which were 167.11°, 141.87° and 148.78° respectively, caused participants to contact the ball at 142.02% of standing height (Table 11). A resultant ball velocity of 36.14 m/s followed after these events, the standard deviation value again reinforce the amount of variation in post-impact ball speeds between individuals.

Table 10. Three-dimensional angles of the racket side of body at impact (°)

<table>
<thead>
<tr>
<th></th>
<th>Ankle</th>
<th>Knee</th>
<th>Hip</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>138.06</td>
<td>167.11</td>
<td>141.87</td>
<td>117.20</td>
<td>148.78</td>
<td>154.22</td>
</tr>
<tr>
<td>SD</td>
<td>6.41</td>
<td>9.57</td>
<td>5.83</td>
<td>11.45</td>
<td>12.37</td>
<td>6.26</td>
</tr>
</tbody>
</table>

Table 11. Ball Movement at impact

<table>
<thead>
<tr>
<th></th>
<th>Post-impact ball speed (m/s)</th>
<th>L impact (m)</th>
<th>H impact (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>36.14</td>
<td>0.75</td>
<td>142.36</td>
</tr>
<tr>
<td>SD</td>
<td>4.05</td>
<td>0.09</td>
<td>5.52</td>
</tr>
</tbody>
</table>

*L impact = difference between impact height and players standing height. H impact = impact height relative to standing height.*
Figure 5 shows the resultant velocities at the hip, shoulder, elbow, wrist and racket for the top ranked player. A proximal to distal sequence of movements is evident and was consistent for all participants.

Figure 5. Resultant linear velocities of the hip, shoulder, elbow, wrist and racket after leg drive initiation for the highest ranked player.
CHAPTER FOUR
DISCUSSION
Discussion

Coaches are continually required to observe technique and provide feedback on ways to enhance performance (Bartlett, 1999). This study aimed to examine the influence of the ground reaction force and joint kinematics on the performance of the tennis serve in collegiate players. It was thought that quantifying these elements to compare against a model performance would be beneficial for player development and coaching methods. In a similar way to the review of literature, the following pages have been sectioned into the lower limb and upper limb. The upper extremity has been further broken down into the backswing, the acceleration phase and impact.

4.1 Leg Drive

Eight collegiate performers produced a mean vertical ground reaction force of 2.26 BW. This was consistent with studies of a similar nature (Girard et al., 2007; Girard et al., 2005) and in line with Elliott and Wood (1983) who reported that peak vertical forces can be up to 2 BW. The mean peak vertical force was greater than the 2.12 BW reported for nationally ranked French players (Girard et al., 2007). A larger GRF will allow more rapid acceleration towards the ball. This type of GRF has been shown to create an impulse at an angle from the centre of mass, essential for the transfer of angular momentum from the legs to the upper extremity (Girard et al., 2005). By creating a larger GRF relative to body weight, it could be therefore assumed that the eight participants have an increased potential to develop racket head speed compared to the players in the study by Girard et al. (2007) mentioned above given that the players were of similar mass. The GRF propelled the participants vertically by a mean value of 0.06 m enabling them to impact the ball at 142.63 % of their relative standing height; this was due to the gain in momentum throughout the service action rather than a conscious decision to leave the floor (Elliott et al., 1986). Being able to contact the ball at greater height will reduce the amount of service box blocked by the net, therefore increasing the margin for error (Chow et al., 2003).
Elliott and Wood (1983) investigated the variations in the ground reaction force curves of the foot-up (FU) and foot-back (FB) serve techniques. Using a FU style has been shown to generate larger vertical forces subsequently displacing the server further in the vertical direction, while the FB technique generates larger horizontal forces. While the FU style did generate a higher GRF (2.26 BW) this was only minimal (FB = 2.25 BW) and therefore neither statistically or practically meaningful. This could be attributed to the fact there was only one participant who adopted the FB technique out of the eight and given that he was the second highest ranked player, it could be expected that he would produce higher GRF than the six lower ranked participants using the FU style. This reinforces that the following brief section comparing FU and FB technique which does display some interesting findings, should be treated with caution.

The FU group were driven vertically by 0.07 m at ball contact, causing them to impact the ball at a greater height relative to their standing height (142.61 %) in contrast to the player using a FB technique (138.58 %). The FB style too displaced the performer vertically although not as notably (0.01 m) however this technique was more characterised by the distance the server found themselves into the court. By the time the participant finished their serve they were 0.67 m in front of the baseline, this value was greater than for the FU style (0.62 m). The FB technique has been associated with larger propulsive force in the horizontal (Fy) component (Girard et al., 2007). The FU stance produced greater peak knee joint flexion in both the front (69.9°) and rear leg (81.0°) compared to the FB technique (front leg = 63.8°; rear leg = 60.6°). The front leg result is somewhat surprising given that the wider base linked with the FB stance allows for an increased squat depth (Reid et al., 2008). Previous research has also found front knee flexion to be larger with the FB stance; Reid et al. (2008) reported values of 85.7° for the FB stance and 69.9° for the FU. The same authors however revealed rear leg flexion to be larger in the FU stance (59.4°) in contrast to the FB stance (44.8°), in agreement with the current study. This result when paired with greater peak angular velocity of rear knee extension in the FU stance previously reported (Reid et al., 2008) goes someway in explaining the higher vertical ground reaction forces for this technique.
Despite this the amount of front knee flexion displayed in both the FU and FB stances was similar to those found by Bartlett, Piller and Miller (1994) and were in line with the $70^\circ \pm 10^\circ$ range of acceptability proposed by Elliott (2003). While it has been shown that stance is ultimately a matter of personal choice due to no difference in outcome velocity (Elliott and Wood, 1983) there are certain implications which could affect a player's tactics. While the FU technique may produce greater vertical force, it also requires greater horizontal braking forces (Girard et al., 2007), impeding the players ability to rush to the net. Therefore a FB technique, which has been shown to produce greater horizontal forces, favours rapid displacement to the net (Girard et al., 2005) and so may be more desired for a player of this nature.

4.2 Backswing

Following the use of one of the two stance and as the knees begin to flex, each participant moved the racket downward behind their back in what Elliott et al. (1986) described as a looped backswing. This movement was said to be a direct product of the shoulder turn, leg drive and gravity (Elliott and Kilderry, 1983) and its effectiveness is dependent on the amount of shoulder turn (Bradon and Bruns, 1977). During the backswing participants in the present study decreased their elbow angle to a mean minimum value of 50.66°, highlighting that full flexion of this joint did not occur but rather the humerus was rotated when in an abducted position (Elliott et al., 1986). The elbow has an important role in stabilising the surrounding muscles to improve service accuracy (Correla and Veloso, 1998).

The current study also reinforced the value of an active leg drive in forcing the racket down and away from the back ready for the acceleration phase. After the commencement of the leg drive the hip and shoulder were driven vertically at mean velocities of 2.31 m/s and 2.68 m/s respectively, during this process the racket was travelling downward at a mean velocity of -5.23 m/s. While data for these variables was not reported in a study on world class players (Fleisig et al., 2003) preventing comparisons to the desired performance, Elliott et al. (1986) did state the vertical velocities of body segments for players of similar standard to the current study. They experienced mean vertical velocities of 1.5 m/s at the hip and
1.8 m/s at the shoulder. This finding reinforces that the current participants completed a leg drive that was effective in transferring energy and momentum from the legs, through the trunk and up to the racket limb (shoulder).

At this time the highest ranked player was more able to produce a downward racket velocity (-5.32 m/s) much closer to that of his maximum (-6.19 m/s). This was in contrast to the lowest ranked player who in the same process generated a racket velocity of -2.32 m/s when his maximum was -13.17 m/s. Put more simply, the highest ranked player was more able to coincide the time when his hip was at maximum vertical velocity with when his racket was at maximal velocity in the opposite direction thus increasing the distance the racket has to travel to ball impact. Improving the angular displacement of the racket will consequently allow for higher racket head velocity (Girard et al., 2007) as well as enhancing external rotation of the shoulder (Elliot, 2006). The lowest ranked players backswing initially involved a lot of movement (-13 m/s) suggesting it was somewhat erratic and rushed, but then this lessoned (-2.32 m/s) as the trunk was driven vertically. A lack of fluent motion in this participant will have a detrimental effect on performance and increase injury potential (Elliott, 2006). Nevertheless all eight participants were observed to eccentrically pre-stretch the internal rotator muscles by positioning the racket down behind the back. This acts as a countermovement prior to internal rotation as the racket begins to accelerate towards the ball (Girard et al., 2005).

4.3 Acceleration Phase

As the racket is maximally displaced behind that back, a product of shoulder abduction, shoulder external rotation, elbow flexion and wrist extension concludes with the racket almost parallel with the trunk (Fleisig et al., 2003). At this moment in time the performer has achieved maximal external rotation of the shoulder and from this point forward there was a rapid series of movements as the racket begins to accelerate towards impact. High racket speed can only be generated following the coordinated movements of adjoining body segments (Elliott, 2006).
By quantifying the velocity of body segments the current study was able to define a kinetic chain in all performers. The resultant linear velocities of the knee, hip, shoulder, elbow, wrist and racket segments increased in a proximal to distal sequence prior to impact. This supports the results found in many studies that also identified an increase in resultant velocity from the knee up to the racket (Liu et al., 2010; Putnam, 1993; De Subijana and Navarro, 2009), however goes against the findings of Sciaccia and Kibler (2006) who stated that maximum elbow velocity was achieved prior to maximum shoulder velocity. Figure 5 shows the resultant linear velocities of the top rated performer from the start of lower limb drive up to a few frames after ball contact. The proximal to distal sequencing is evident to see with each segment working in harmony to develop end point racket head speed. While this was observed in all participants, the different timings between all eight players meant segment velocities could not be averaged and so this is the rationale for displaying the top performer only.

Following flexion of the shoulder, the elbow extended to produce a mean maximum resultant velocity at the end of the segment of 8.85 m/s at 0.05 seconds before ball contact. Energy was further transferred as the wrist flexed to generate a maximum resultant velocity of 31.06 m/s at the top of the racket head 0.02 seconds before ball contact. These values were slightly less but in line with those of Gordon and Dapena (2006) for a group of intercollegiate tennis players (13.5 m/s and 47.4 m/s respectively). Extension of the forearm has been said to have an increased role in a ‘kick serve’ nevertheless it is important in raising the height of contact (Elliott et al., 1995), which naturally occurs during long axis rotation, and transferring the forces generated by the trunk to the ball at contact via the racket (Correla and Veloso, 1998).

Although not quantified, pronation of the forearm occurred in all eight participants around the same time as wrist flexion. While this is has been shown to have a negative (Gordon and Daphna, 2006) contribution towards the development racket head speed, trying to eliminate it will have a severe detrimental effect on performance given that it is necessary in order to angle the racket face at contact so that ball travels in the correct direction (Elliott et al., 1995). The focus rather
should be on completing the pronation as much as possible before contact which has been associated with higher racket head speed (Elliott et al., 1995).

The prevalence of injury has been associated with a dysfunctional kinetic chain function (Kibler and Sciascia, 2004). While it may be expected performers of an elite level have been proven to show a solid kinetic chain (Chow et al., 2003), amateur performers have been shown to generate distorted contributions from different body segments (Sprigings et al., 1994). It is a sign of encouragement that the collegiate performers here were able to perform a serve with a functional kinetic chain (Figure 1), in that the velocities of each segment progressively attained their maximum. While internal loads at the elbow were not measured, it is likely that these would have been reduced due to an effective sequencing from the legs. An awareness that players are competing with a reduced potential for injury means that performance can be more focused upon in training rather than having to alter technique.

4.4 Impact

Peak resultant racket velocity at impact for this study was 30.92 m/s. This value was similar to the 31.0 m/s reported by Elliott et al. (1995) who studied amateur tennis players but naturally less than that of elite performers (38.57 m/s) (Chow et al., 2003) and more than a Australian performer whose serve was identified as lacking speed (27 m/s) (Sprigings et al., 1994).

The product of lower leg drive and trunk rotation resulted in a vertical velocity of 2.55 m/s of the racket shoulder at contact (Table 6). This dropped from a peak value of 4.02 m/s achieved 0.12 s before impact. This result is consistent with other studies that upon impact generated a racket shoulder velocities of 3.0 m/s (Elliott et al., 1995), 2.0 m/s (Sprigings et al., 1994) and 2.5 m/s (Van Gheluwe and Hebbelinck, 1985) contributing 9.7%, 7.4% and 8% to racket head speed respectively.
The mean shoulder abduction angle at the moment ball contact for the eight participants was 117°. This was greater than the 101° angle created by Olympic athletes (Fleisg et al., 2003) but less than for nationally ranked players (Elliott et al., 1986). Furthermore it is slightly larger than the optimal angle of 100° ± 10° recommended by (Elliott, 2003) and greater than the self-optimising angle of 90-100° suggested to generate maximum ball velocity in baseball pitching (Matsuo, Matsumoto, Takada and Mochizuki, 1999). Reilly, Amis, Wallace and Emery (2003) established that once the shoulder abduction angle increases beyond 120° considerable strain is put on the supraspinatus tendon in such a way that could cause failure.

The mean elbow angle at contact was shown to be 148.78°; this value was similar in nature to that of collegiate players (157°) (Elliott et al., 1986) and of elite performers (160°) (Fleisg et al., 2003). The elbow therefore was not fully extended to 180°. This was the case also at the knee (167.11°), hip (141.87°) and wrist (154.22°) which, although extended, did not reach the fully extended angle of 180° to produce maximum contact height. This highlights that the eight participants were leaning forward into the court at impact, a consequence of the shoulder over shoulder and forward rotations associated with service motion (Elliott, 2006).

Prior to contact the ball dropped 0.65 m from a peak ball height of 3.19 m. This was greater than previous findings of 0.51 m (Elliott et al., 1986) and 0.27 m (Plagenhoef, 1970). Subsequently ball velocity at impact was 3.71 m/s; double the 1.8 m/s presented by Beerman and Sher (1981) when the ball dropped 0.15 m. Brody, Cross and Linsday (2002) found that a ball toss 0.15 m above impact will increase the service success rate by 12 %. They did not report findings of ball toss over the height of 0.19 m however, it could be assumed that by increasing the height and subsequently the time the player has to impact, the more opportunity they have to better prepare (backswing) and execute (acceleration phase) the shot. However with elite performers impacting the ball from a drop of 0.27 m (Plagenhoef, 1970) it may be possible that there is an optimum height, past which too much time will be detrimental to performance; a possible avenue for further research.
The ball was contacted at mean height of 2.54 m off the ground; less than 2.74 m (Chow et al., 2003) and 2.66 m (Elliott et al., 1986) previously reported. While elite players should aim to hit the ball downwards into the service box (Brechbuhl, Tieche and Frey, 2001) this was not possible for the current group of players given their impact height (2.54 m). Braden and Bruns (1977) found that even for an impact height of 2.7 m the player was unable to hit with a downward trajectory. Therefore the ball would have had to been hit slightly upwards initially in order to get over the net sacrificing ball velocity. The height of impact is crucial and the advantages of being taller when serving are therefore evident.

Resultant ball velocity post impact was recorded at 36.14 m/s. As expected this was considerably lower than Olympic performers (50.8 m/s) analysed by Fleisig et al. (2003). When compared to ball velocities of 42.4 m/s generated from players of a similar standard (Elliott et al., 1986) the current participants serves are lacking speed. Furthermore the ball velocity is less than 44 m/s; a value which has been shown to produce more errors from the player returning (Haake et al., 2000). Given that the current group of players produced effective levels of knee flexion and subsequent GRF, it may be suggested that for some individuals their kinetic chain was not as functional towards the distal segment, in particular from the shoulder upwards. It is therefore recommended that focus on training should involve the interaction of the shoulder, elbow, wrist and racket however further more in depth research into upper limb activity is required to confirm this.

4.5 Limitations

Like many forms of biomechanical analysis, the process of digitising is human controlled and irrespective of intra observer reliability, there are more than likely going to be inaccuracies associated with it. It must be stressed however that the misidentification of joint centres, which contributes a large amount to these errors, was accounted for and minimised through reliability testing. For some individuals the racket went out of view during the back swing in camera two for a few frames. While the operator was able to make an educated guess as to the racket’s position, this may explain the larger RMSD accuracy scores. To avoid this future, the use of three cameras would considerably improve visualisation of anatomical
landmarks from that of two cameras and enhance the 3D reconstruction process. While the picture quality was adequate for a study of this nature, it could have been a limitation. When using the zoom function especially the picture quality deteriorated significantly, for future research better images may produce more accurate results. Furthermore a consequence of filming at a frequency of 50Hz meant that results were only accurate to 0.02 seconds. Therefore at ball contact for example, which is instantaneous, the likelihood of error will increase.

Although not the prime focus of the study, the comparisons between FU and FB were somewhat inconsequential and limited given that there was only one FB participant. Ideally there would have been an equal number of each stance for analysis to provide much more substance to the findings, however since this was only a minor section of the study it did not hold too much of a negative influence. Finally it should be mentioned that modelling the limbs and racket as solid objects also limits the results. As such rotations are not taken into account which have been shown to be some of the biggest contributors to racket head speed (Elliott et al., 1995).

4.6 Future research

The repetitive nature of certain ground stokes and the serve especially increases the potential in many performers of overuse injuries which are one of the main tennis injuries reported (Pluim, 2004). Future research into quantifying the internal loads i.e. joint torques on collegiate players can be used to better understand the demands placed upon the body and may help identify the performers who are predisposed to injury.

The current study has only used kinetic and kinematic data. Hirashima, Kadota, Sakurai, Kudo and Ohtsuki (2001) identified the need to consider the neuromuscular mechanisms involved in the tennis serve. A greater knowledge of the successive muscle activation involved in the tennis serve will further help reduce injury and aid the rehabilitation process in injured athletes (Ryu, McCormick, Jobe, Moynes and Antonelli, 1988). Furthermore by giving information
on the state of the muscle in collegiate players, it can be used in comparison to that of elite athletes in order to facilitate progression.

This study reduced the effect of over smoothing of the racket and ball velocity associated with impact sports by choosing not to include data at the racket and ball in the smoothing program. While this reduced systematic error, it is not ideal and it would be beneficial if focus was put on designing a data smoothing system that could account for the whole body and racket movement collectively.

4.7 Conclusion

Few studies have considered both the upper and lower extremities when analysing the tennis serve, especially in collegiate performers. This study analysed how the kinematics and kinetics of the serve influenced performance in eight university tennis players. In summary, participants showed effective peak flexion angles and generated large ground reaction forces relative to their body weight. The importance of leg drive was highlighted in initiating a proximal to distal sequencing of body segments while placing the racket behind the back in preparation for the forward swing. The highest ranked better player was shown to better coincide the maximum vertical velocity of their hip with the maximum negative vertical velocity of their racket therefore increasing the angular displacement of the racket subsequently increasing racket head speed. While it may be expected racket head speed and resultant ball speed were lacking in comparison to elite performers, they were also less than for performers of a similar standard. Nevertheless a functional kinetic chain gives scope for these areas to be developed. Providing a better understanding of the mechanics involved in collegiate tennis will allow for certain modifications to be made and result in performance enhancement from intermediate to higher levels.
REFERENCE LIST
References


APPENDICIES
Appendix A

CARDIFF METROPOLITAN
INFORMED CONSENT FORM

CSS Reference No:

Title of Project: Ground reaction force and joint kinematics impact on the mechanics of the tennis serve in collegiate players

Name of Researcher: Skene Matthews

Participant to complete this section: Please initial each box.

1. I confirm that I have read and understand the information sheet dated ………. for this evaluation study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that my participation is voluntary and that it is possible to stop taking part at any time, without giving a reason.

3. I also understand that if this happens, our relationships with the Cardiff Metropolitan University, or our legal rights will not be affected.

4. I understand that information from the study may be used for reporting purposes, but I will not be identified.

5. I agree to take part in this study on the role GRF and joint kinematics play in the mechanics of a tennis serve.

__________________________________
Name of Participant

________________________________________________
Signature of Participant
Date

________________________________________________
Name of person taking consent
Date

________________________________________________
Signature of person taking consent

* When completed, one copy for participant and one copy for researcher’s files.
Appendix B
Cardiff School of Sport Ethics Committee
Research Participant Information Sheet

**Project Title:** Ground reaction force and joint kinematics impact on the mechanics of the tennis serve in collegiate players.

This document provides a run through of:

1) the background and aim of the research,
2) my role as the researcher,
3) your role as a participant,
4) benefits of taking part,
5) how data will be collected, and
6) how the data / research will be used.

The purpose of this document is to assist you in making an **informed** decision about whether you wish to be included in the project, and to promote transparency in the research process.

1) **Background and aims of the research**
The serve is one of the most important shots in tennis. Previous research has identified how ground reaction forces produce angular and linear momentum to drive body segments forwards or backwards changing their velocity. Understanding how these kinetic and kinematic factors influence serve effectiveness is important for players and coaches in order to be successful. We (me and my research team) wish to analyses how ground reaction force and joint kinematics impact on the mechanics of the tennis serve of collegiate athletes.

2) **My role as the researcher:**
The project involves me (Skene Matthews), the researcher, organising your involvement in testing and then carrying out the subsequent procedures.

3) **Your role as a participant:**
Your role is to complete the testing to the best of your ability. After completing a warm up you will be asked to perform five serves into a target area. You won’t be required to do anything you wouldn’t habitually do in training or competition.

4) **Benefits of taking part:**
The information we obtain from this study will allow better insight into the role ground reaction force and joint kinematics play in the mechanics of tennis serve in collegiate players. A greater understanding of serving mechanics at the intermediate/advanced level will help coaches and players develop to a higher standard of play. We will be happy to share this information to any of the participants of this study.

5) **How data will be collected:**
Data will be collected via video camera for 3D analysis. Furthermore serves will be carried out on a Kistler force plate which will capture ground reaction force data.

6) **How the data / research will be used:**
In agreeing to become a **voluntary** participant, you will be allowing me to use your service data and include them within a larger data set that includes the data of other participants. Your personal data will be anonymous and will not be reported alone, but within the total sample of participants.

**Your rights**

Your right as a **voluntary** participant is that you are free to enter or withdraw from the study at any time. This simply means that you are in full control of the part you play in informing the research, and what **anonymous** information is used in its final reporting.
Protection to privacy

Concerted efforts will be made to hide your identity in any written transcripts, notes, and associated documentation that inform the research and its findings. Furthermore, any personal information about you will remain confidential according to the guidelines of the Data Protection Act (1998).

Contact

If you require any further details, or have any outstanding queries, feel free to contact me on the details printed below.

Skene Matthews  ST10001869@uwic.ac.uk