An investigation to determine the kinematic variables associated with the production of topspin in the tennis groundstrokes.

by

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A thesis submitted in partial fulfilment for the requirements of the degree of Doctor of Philosophy at the University of Central Lancashire

Volume 1 of 1

August 2011

University of Central Lancashire

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ABSTRACT

The ability to impart topspin to the ball when playing forehand and backhand groundstrokes can give a tennis player a tactical advantage in a rally. Recent developments in racket technology and tactical approaches to the game have increased the prevalence of topspin strokes. However, there is a limited scientific knowledge base for players and coaches to draw upon when seeking to improve this aspect of the game. Many of the kinematic analyses into tennis groundstrokes were conducted more than ten years ago, with measurement techniques that may not have accurately measured the anatomical rotations important for generating racket velocity. It has only recently been possible to measure the spin rate of a ball, and this has not been investigated in relation to the kinematics of a player. This study aimed to make an important contribution to the knowledge of tennis professionals by establishing which kinematic variables are related to the production of high ball spin rates resulting from topspin strokes.

In order to achieve this aim, consideration was given to the accurate measurement of the joint rotations of the player in all planes of movement and the quantification of the ball spin rate. This information was used to answer three further questions; what are the kinematic differences between flat and topspin groundstrokes, how do these differences relate to the spin rate of the ball and how do these findings relate to individual players?

Joint rotations were calculated based on three-dimensional data captured from twenty participants playing flat and topspin forehand and backhand strokes. The resulting ball spin rate was captured using a high-speed camera.

The participants produced larger ball spin rates when playing the topspin strokes, indicating that they were able to produce spin if required. Analysis of the joint rotations revealed that there were adaptations in the stroke in order to achieve the higher spin rates. The adaptations were not uniform among participants, but did produce similar alterations in racket trajectory, inclination and velocity for the topspin strokes. It was these measures that were found to be the strongest predictors of ball spin rates, accounting for over 60 % of the variation in ball spin rate in the forehand stroke and over

70% in the backhand. Case study analyses confirmed the importance of the optimal racket kinematics at impact and provided models of technique throughout the forward swing of each stroke.

This study has made a contribution to the knowledge of generating topspin in the tennis groundstrokes by establishing the parameters that predict high spin rates and applying them to analyses of individual players. In doing so, this investigation has also demonstrated methodology that is capable of accurately measuring the joint rotations associated with tennis strokes, and suggested a method by which the spin rate of the ball can be calculated.

I have been very fortunate to benefit from first rate supervision and support throughout the course of this investigation, without which I would not have made it to the end.

I would like to thank my director of studies David Fewtrell for his help throughout. In particular I would like to thank him for his willingness to engage in a number of informal meetings he was bombarded with. This really helped to keep things moving forward for me. I would like to thank Jim Richards for his advice in the early stages of the project regarding some of the more technical aspects, and latterly his encouragement in the final stages. I would like to thank James Selfe for his sense of perspective throughout, reminding me to see the bigger picture and ensuring I did not fall into the trap of being too ‘geeky’.

In addition to the academic support I have received, the support I have received from friends and family has also been a great source of motivation. There are many people that fall into this category, but I would particularly like to thank my Mum for her encouragement throughout, particularly at the start, and my Dad and Angela for knowing when and when not to ask how I was doing! Finally, and by no means least, thank you to my wonderfully understanding girlfriend Sandy for your continuous support, encouragement and for putting up with my occasional grumpiness!

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ABBREVIATIONS AND DEFINITIONS

2D – two dimensions. Analysis of movement in two dimensions, limits scope of movements that can be measured and may suffer from inaccuracies from out of plane movements.

3D – three-dimensions. Analysis of movement in three dimensions, allowing movement in each cardinal plane to be measured.

6 DOF - Six-degrees-of-freedom. Translational and rotational movement at a joint. There is one translation and one rotation about three orthogonal axes.

BALL SPIN RATE – The spin velocity of the tennis ball.

CARDAN/EULER ANGLES (SEQUENCES) – Ordered sequences of rotations about each coordinate axis that describe one local coordinate system in relation to another. The aim of this is to produce three angles describing the relative position of body segments that have anatomical relevance. This generally refers to flexion-extension, abduction-adduction and internal-external rotation. Changing the sequence of rotations about each axis will produce different kinematics, therefore the order in which they are performed is important. There are six Cardan angles that are characterised by rotations about each axis, and the six Euler angles rotate about only two axes with the first and terminal rotation about the same axis.

CAST – Calibrated anatomical systems technique. Measurement technique allowing six-degrees of freedom to be measured at a joint, whilst reducing the relative movement of bone and soft tissue.

COM – Centre of mass. The point whereby the mass of a body segment or object is evenly distributed. Displacement and velocities of the racket and upper limb segments with respect to the global coordinate system were calculated from this point.

CROSS PLANAR TALK – The result of misaligned local coordinate systems that manifests in similar angle patterns across the different planes of motion. Therefore, the angle patterns produced from misaligned axes will include movement from outside the plane of interest. For example, an intended angle plot of abduction may also contain elements of flexion and internal rotation.

DOWNWARD RACKET W.R.T. FOREARM – The downward movement of the racket with respect to the position of the forearm. The kinematics of the wrist were not measured directly, therefore the relative positions of these segments were calculated to provide an estimate of this joint movement.

ELBOW FLEXION-EXTENSION – The rotation of the forearm with respect to the humerus about the sagittal axis. Flexion is defined as the closure of this angle, tending towards zero, whilst extension tends to 180°.

FOREARM PRONATION-SUPINATION – The rotation of the forearm about it's transverse axis in order to rotate the palm of the hand to the posterior (pronation) or to the anterior (supination). This rotation was calculated with respect to the transverse axis of the humerus.

GIMBAL LOCK – Mathematical indetermination of angles due to the second rotation in an angular sequence equalling ± 90°. In this case the first and third axes coincide, thus producing identical angles for the first and third angles in a Cardan / Euler sequence. Gimbal lock can be observed graphically by a discontinuity of the third angle in the sequence, when the second angle tends to ± 90°.

GLOBAL COORDINATE SYSTEM – The coordinate system of the laboratory. This defines the positive sense of the axes in three orthogonal directions, with an origin at (0, 0, 0).

HIP FLEXION-EXTENSION – The rotation of the thigh with respect to the pelvis about the sagittal axis.

HUMERUS ROTATION (INTERNAL-EXTERNAL) – The rotation of the humerus with respect to the trunk about the transverse axis.

ISB – International Society of Biomechanics. International body with the aim to advance biomechanics, and standardise measurement across a number of disciplines.

ITF – International Tennis Federation. The governing body of tennis worldwide.

KNEE FLEXION-EXTENSION – The rotation of the shank with respect to the thigh about the sagittal axis.

LOCAL COORDINATE SYSTEM – Also termed segment coordinate system. This is the coordinate system embedded into a body segment that defines the positive sense of three orthogonal axes. Functionally, these axes coincide with the sagittal, coronal and transverse axes of the body.

MAGNUS FORCE – The force due to the spin of a ball. The difference in velocity between the top and bottom of the ball, creates a pressure differential. This creates a downwards force for a ball hit with topspin, and an upwards force for a ball hit with backspin. The magnitude of the force is dependent on the amount of ball spin, the radius of the ball, the velocity of the ball and the air density.

RACKET ANGLE – The angle of the racket with respect to the horizontal. This is calculated from the inverse tangent of the relative instantaneous vertical and horizontal velocities of the racket centre of mass.

RACKET INCLINATION – The inclination of the racket-head with respect to the vertical axis of the global coordinate system. The racket-head may be inclined either forward (closed) or backward (open).

RACKET LOW-HIGH – The upward displacement of the racket with respect to the vertical axis of the global coordinate system.

RACKET VELOCITY – The linear velocity of the racket with respect to the global coordinate system. This is a vector derived from the velocity in three orthogonal directions.

ROM – Range of motion. The absolute displacement over a given time period.

SHOULDER ABDUCTION-ADDUCTION – The rotation of the humerus with respect to the trunk in the coronal plane. Abduction rotates the arm away from the trunk, whilst adduction moves the arm towards the trunk.

STA – Soft tissue artefact. The relative movement of skin and soft tissue and the underlying bone.

UPWARD RACKET DISPLACEMENT – The upward displacement of the racket during the forward swing. This was taken throughout, yielding either a positive or negative (downward) value, but also prior to impact.

VERTICAL FOREARM VELOCITY – The upward or downward velocity of the forearm centre of mass calculated with respect to the global coordinate system.

VERTICAL RACKET VELOCITY – The upward or downward racket velocity of the centre of mass of the racket calculated with respect to the global coordinate system.

VERTICAL UPPER ARM (HUMERUS) VELOCITY – The upward or downward velocity of the upper arm centre of mass calculated with respect to the global coordinate system.

XYZ. Refers to an order of rotations in determining the angle at a joint, whereby a segment is rotated first about the X axis in order to project onto another set of axes

1. INTRODUCTION

Tennis is a sport that is constantly evolving with improvements in the technology associated with the racket, ball and court surfaces. Developments in racket technology were blamed for a perception of serving dominance 10-15 years ago, particularly in the men's game. The scientific community attempted to quantify this perception by measuring the percentage of sets ending in a tie-break, with the implication that each player held their own serve throughout the set. This measure was shown to have a positive relationship with maximum serve speed, with a linear relationship emerging when ball speeds increased above 120 miles per hour (53.64 $m.s^{-1}$) (Haake *et al.*, 2000). Furthermore, the work of Haake *et al*. (2000) demonstrated an increase in the percentage of sets ending in a tie-break on all surfaces, but markedly on grass, from 1965 to 2000.

The dominance of serve speed prompted the International Tennis Federation (ITF) to attempt to reduce the dominance of the serve to maintain the appeal of tennis to spectators and the media. Measures included a pace rating system to assess court speed and the introduction of a larger ball in 2002 (ITF, nd). Brody (2003) illustrated that players would have to increase racket-head speed by up to 25% to compensate for slower court speeds, whilst a larger ball could increase the time to the receiver by 10 ms (Haake *et al*., 2000). A recent analysis by Takahashi *et al.* (2009) indicated that these alterations have had some success. They reported an increase in rally length, in terms of the number of shots and rally duration in matches studied in the 2000's compared to the 1990's. Whilst the measures in that study are not the same as previous analyses such as Haake *et al*. (2000), it does lend some support to anecdotal evidence that there are more rallies in the men's game compared to 10-15 years ago.

The decrease in the serve's dominance has seemingly placed a greater emphasis on the groundstrokes for winning a point. Imparting topspin on the ball is one way in which a player can gain an advantage in a rally in order to win a point, as a ball hit with topspin will bounce higher off the court. Furthermore, playing with topspin will reduce the chance of a player erring by hitting the ball over the baseline and losing the point, as it has a shorter trajectory than a ball hit without spin would. This is due to the Magnus force acting on the ball due to a pressure differential caused by the difference in velocity of the ball on the top compared with the bottom (Bartlett, 1997). The inverse lift (Magnus) force acting on the ball forces it towards the court at a steeper angle (Cross, 2002b) leading to a larger vertical ground reaction force than a non-spinning ball. Therefore, the ball hit with topspin will bounce higher off the court, making it more difficult to return. This is particularly true of players with a more traditional forehand grip that is more suited for low bounces, and some coaches such as Bollettieri (2001) have recognised this potential tactical advantage. Other coaching texts have cited the variation playing with topspin can bring to a players baseline game (Antoun, 2007), and the control it can give a player over their groundstrokes (Brown, 2004). Due to these advantages topspin groundstrokes are becoming more prevalent in the modern game. However, there is a limited evidence base from biomechanical research for coaches and tennis professionals to base technique enhancement of topspin groundstrokes around. Thus far, there has been no empirical research explicitly linking the magnitude of topspin production to the kinematics of the tennis player when playing these strokes. The challenges related to establishing this link fall, broadly, into two categories; accurately assessing the contribution of joint kinematics to a tennis stroke and the quantification of ball spin.

Three-dimensional analysis of tennis strokes has established joint angles, linear and angular velocities and ball speeds (Lees, 2003). Variables such as grip (Elliott *et al*., 1997) and one and two-handed approaches (Reid and Elliott, 2002) have been identified in addition to overall technique analysis (e.g. Chow *et al*., 2003; Elliott *et al*., 1989; Fleisig *et al.*, 2003). Many of these analyses have concentrated on the generation of end-point velocity at the racket, but have not analysed the generation of spin by the same means. Some kinematic comparisons have been made of players hitting topspin strokes and flatter deliveries, but these strokes have been characterised as flat or topspin by coaches rather than by any quantitative measure. Therefore, whilst some players can undoubtedly produce high levels of spin when playing groundstrokes the mechanisms for hitting a high versus a low amount of spin are not known.

The different measurement techniques used in the analysis of various tennis strokes have thrown up some contention regarding which anatomical rotations contribute most to the development of the stroke. This, and the use of some measurement techniques that may not fully represent the motion of joints across all cardinal planes of movement, leaves some questions still to be answered relating to coaching points for various tennis strokes.

Research relating to the spin of a tennis ball has largely been carried out in wind tunnels by researchers wishing to establish the aerodynamic properties under different conditions. However, there has been little direct measurement of the tennis ball, and none of these measurements have been taken with regard to a player under laboratory conditions. The measurements taken thus far have largely been obtained from players in a match or practice situation. Whilst these measurements have provided some information regarding the capabilities of tennis players at various levels, no data exists where a player has been instructed to hit with a large amount of topspin.

The aim of this study was to develop a methodology of quantifying ball spin alongside the measurement of joint rotations to allow the link between joint movement when playing tennis strokes and the amount of ball spin to be investigated.

Thesis Structure

Chapter 1: Introduction. The historical perspective for the importance of topspin in the modern groundstroke is provided before a brief outline of the research undertaken thus far and the challenges related to quantifying ball spin in relation to the kinematics of the player.

Chapter 2: Review of the literature. In depth review of the limitations of existing research related to the measurement of kinematics and ball spin. A review of relevant findings in relation to the tennis groundstrokes then follows leading to the aim and objectives of the research.

Chapter 3: Development of Methods. The developmental work undertaken with respect to the measurement of the kinematics of tennis strokes and ball spin.

Chapter 4: Main Methods of Analysis. The measurement techniques used experimental procedures and methods of analysis in relation to the main study.

Chapter 5: Results: Investigation of differences between forehand and backhand top spin and flat shots. Kinematic differences between the two types of tennis forehand and backhand strokes are presented in turn.

Chapter 6: Results: Investigation of relationship between the amount of topspin and joint kinematics for forehand and backhand shots. The relationship between topspin and key kinematic variables is explored for each stroke in turn.

Chapter 7: Results : Case Study Analysis of players producing in excess of 2000 $rev.min^{-1}$ of ball spin. The kinematics of a selection of players producing a high amount of topspin is investigated to establish some principles of best practice.

Chapter 8: Conclusions and Further Work. Conclusions are drawn based on the results of the preceding three chapters, recommendations to coaches and tennis professionals and future developments in this research area are identified.

2. REVIEW OF LITERATURE

This critical review will examine the challenges related to accurate quantification of joint motion in all three cardinal planes and the development of methods to record the spin of a tennis ball. It will then focus on the relevant research in the kinematics of tennis groundstrokes.

2.1 LIMITATIONS OF CURRENT KINEMATIC ANALYSES OF TENNIS

Kinematic analyses have enabled biomechanists to develop some understanding of the movement patterns required for successful tennis strokes. However, there are differences in the methods used in this area of research that have led to varying interpretations of which body segments are largely responsible for the generation of end-point racket velocity in many strokes (Lees, 2003). A lack of standardisation of methods in this area of research is an obvious limitation. This section examines the limitations of the kinematic analyses of tennis strokes to date. It begins by discussing the various technology used to analyse tennis strokes, then the marker set ups used to recreate the movement of the player. The section concludes by summarising the impact of these limitations on kinematic analyses to date.

Many analyses of the tennis groundstrokes have been undertaken using two or more video cameras to record two-dimensional angles in the sagittal, coronal and transverse planes based on a small number of reflective markers placed at relevant anatomical positions (Rogowski *et al*., 2007). This does not constitute a true three-dimensional analysis (Hamill and Selbie, 2004), it is analysis of two-dimensional angles from multiple perspectives and is subject to errors due to camera placement relative to the axis of interest (Nigg *et al.*, 2007). The error associated with video-based techniques is the digitisation of the anatomical landmarks to a suitable degree of accuracy. Historically, most video-based systems require a vast amount of manual coordinate digitisation (Bartlett, 1997) which requires users to manually identify the anatomical landmarks in each frame of data. This is very time consuming and introduces a source of human error. Although few studies have directly reported manual digitisation, the widespread use of video makes it likely that many others have employed this technique. Research using automatic digitisation still carries further errors including the resolution of the coordinate digitiser and parallax and perspective errors (Bartlett, 1997). The issue of perspective and parallax error is particularly relevant to all video-based measurements. These errors increase when the recorded movement takes place across planes of motion and analysis of the kinematic data is to take place outside of the sagittal plane. This is very much the case with the tennis groundstrokes. The time consuming nature of digitisation of video has meant that some studies investigating tennis strokes have based their findings on two participants (Groppel *et al.*, 1983) or from analyses of only one trial per participant (Elliott *et al.*, 1989a). The former approach makes the assumption that a small sample is representative of the wider tennis population, thus leaving limited scope for a variety of techniques, whilst the latter assumes a single trial is representative of a player's performance. Knudson (1990) demonstrated the limitation of the later approach in his intra-subject analysis of the tennis forehand. He found coefficients of variability of 90.6 % for angular velocities and 129.5 % for angular accelerations at the wrist and elbow joints. This highlights the inherent variability in tennis strokes, therefore research with a small number of trials or participants may struggle to separate whether variability is due to meaningful differences in technique or natural variation associated with open-skills. This may be particularly important if an investigation is attempting to gain an insight into kinematic differences between two or more types of stroke. It has been demonstrated that five trials is sufficient to establish consistent angular kinematic data in tennis strokes (Knudson and Blackwell, 2005). Therefore, some previous studies examining differences between types of tennis stroke, using a small number of trials, should be interpreted with caution.

Recent development of optoelectronic systems has provided the possibility of overcoming the errors described above through automated tracking by multiple cameras at higher frame rates. The automation of these systems allows a large number of cameras to capture the movement, with limited processing (Pedotti and Ferrigno, 1995). The increased number of cameras, commonly used with optoelectronic systems, increases the chance of a marker being tracked throughout a complex movement with a reduced three dimensional error (Richards *et al.*, 2008).

Optoelectronic systems also allow the reflective markers, placed on a participant, to be identified without human intervention (Pedotti and Ferrigno, 1995). However, there are advantages and disadvantages to this. Whilst automatic identification eliminates human error, the markers do need to be labelled correctly by the user. Furthermore, errors can arise from split or overlapping marker trajectories, which require intelligent processing on the part of the user (Pedotti and Ferrigno, 1995). Other limitations of automated tracking are that markers may move relative to the underlying anatomical position and that the centroid of a marker may not always be seen by a camera, and therefore be miscalculated (Bartlett, 2000). These errors might be reduced through intelligent identification of a joint centre using manual digitisation (Bartlett, 2000), however this would depend on good image quality.

The automation that optoelectronic systems provide allows complex movements, such as tennis groundstrokes, to be captured accurately using a high number of cameras. Allied to modern computing systems, a large number of markers can be tracked at high frame rates in a limited time. Despite some limitations with automated tracking of markers, this gives such systems considerable advantages over video-based analyses in terms of the accuracy and speed at which tennis groundstrokes can be captured.

The models used in much of the kinematic research in tennis can be characterised as two-dimensional reconstructions that attempt to answer problems in three-dimensions. Such reconstructions are derived from the use of simple marker sets, whereby a single marker is placed on the anatomical joint of interest (Richards and Thewlis, 2008). The approach may be suitable for an analysis of movement in the sagittal plane, but movements in the coronal and transverse planes can not be calculated through a simple anatomical marker set (Richards and Thewlis, 2008). These movements are believed to be important in the generation of end-point velocity for a number of racket sports (Marshall and Elliott, 2000), particularly the axial rotation of the upper limb segments. Therefore, the use of simple marker sets only has limited scope in describing the effectiveness of various anatomical rotations to produce racket velocity, or ball spin.

The marker system used for the algorithm developed by Sprigings *et al.* (1994) (Figure 2.1) and subsequently Elliott and co-workers (1995, 1997 and 2000) represented an extension of the aforementioned analysis. The joint centres were constructed from the computerised mid-point of each pair of markers (Sprigings *et al.*, 1994) to form a two-dimensional model of the arm. Four main segments (upper arm, forearm, hand and racket) are constructed from ten reference markers on calculated anatomical positions (Figure 2.1) to produce movements of flexion-extension, abduction-adduction and internal-external rotation. The relative (anatomical) rotations of each segment are calculated from the absolute angular velocity of each segment. Whilst it is an extension of a simple planar analysis, this approach does not compute the three-dimensional angle with consideration of all degrees-of-freedom at the joint simultaneously.

Studies using a limited number of markers (Figure 2.1) are also more likely to be affected by soft tissue artefact (STA), particularly for movement in the coronal and transverse planes (Leardini *et al.*, 2005). This is defined as the movement of soft tissue relative to the underlying bone and is an issue affecting all analyses of human movement using surface mounted markers. STA is compounded by methods which use two co-linear points in describing rotations about the longitudinal axis. It is constrained by the requirement to accurately place markers at the precise landmark, irrespective of the amount of STA likely to occur at that site. STA has been shown to be velocity-dependant (Leardini *et al*., 2005), therefore it is possible that the movement of soft tissue is greatest at the end-point of segments where velocities are highest in activities with a proximal-to-distal sequence.

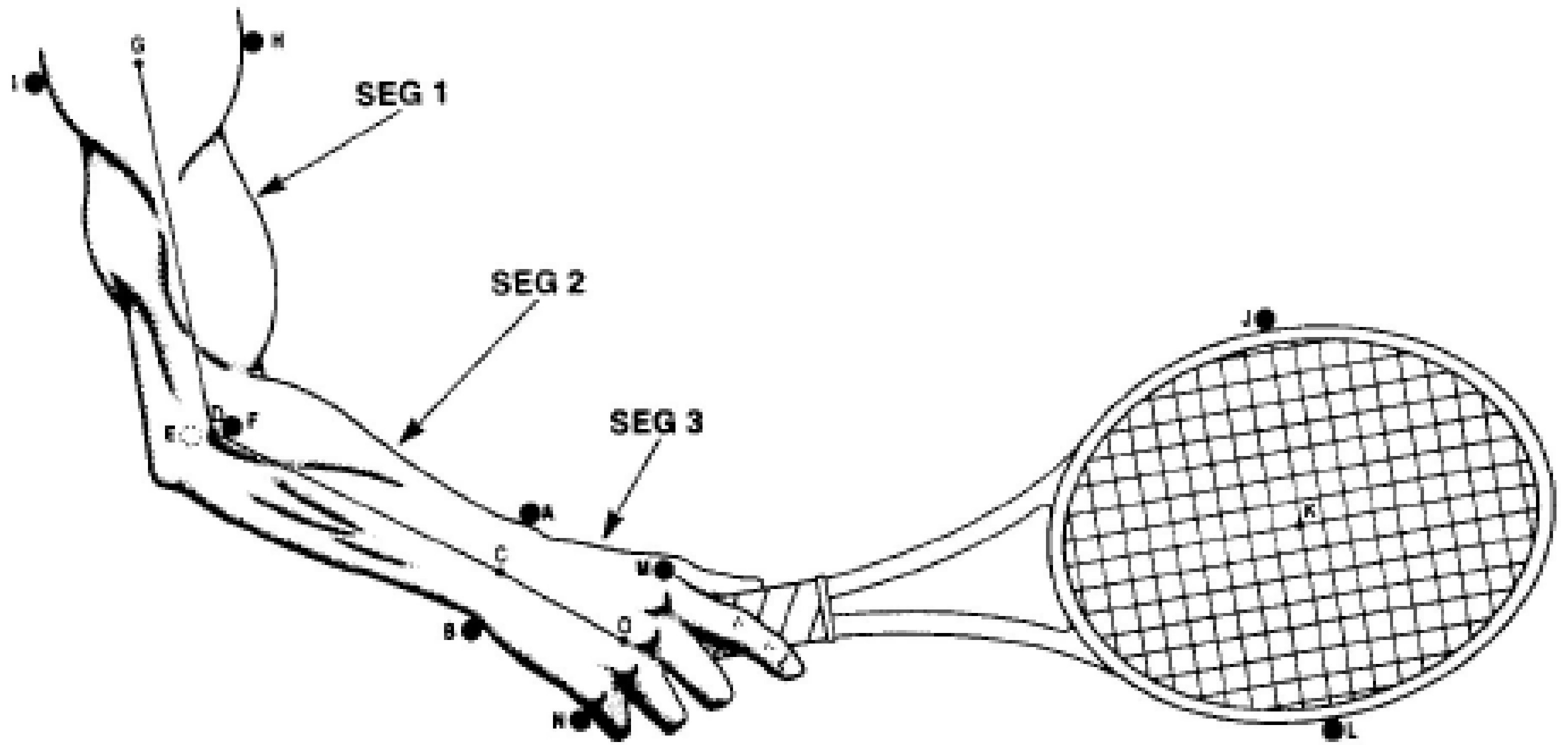


Figure 2.1 – Construction of the segments used in an algorithm to determine the effectiveness of arm segment rotations. Points H, I, E, F, B, A, N, M, L and J are reference markers whilst points G, D, C, O and K are the computed mid-points between each pair. (Taken from Sprigings *et al.*, 1994).

The calculation of the true three-dimensional angle is considered the gold-standard in the description of human kinematics (Hamill and Selbie, 2004) as the relative position of a body segment can be calculated with respect to another at any point in three-dimensional space. This entails the creation of a local coordinate system within a rigid body, and therefore preserves the coordinates at a fixed point within the system, (Zatsiorsky, 1998). Rigid-body modelling using a separate cluster of markers to track the movement of a body segment has recently been adopted for analysis of the tennis serve in a study by Gordon and Dapena (2006). This type of modelling, known as the 'Calibrated Anatomical Systems Technique' (CAST) (Cappozzo *et al*., 1995), could overcome the limitations of previous research in this area. It was developed to account for different experimental protocols allowing for the same data processing and definitions of variables. A global coordinate system is defined and related to the local coordinate system of a segment (Figure 2.2). This part of the technique is no different from any other procedure reconstructing coordinates in space. The difference with CAST is the construction of two local coordinate systems in reference to each other for each segment under consideration. These are the cluster technical frame and the anatomical frame (Cappozzo *et al*., 2005).

The technique references the positions of at least three rigidly connected non co-linear markers (the cluster technical frame) on each segment to the anatomical markers that define the segment at proximal and distal ends (the anatomical technical frame). Once a static calibration has been captured the anatomical markers are removed for the capture of the movement. Software used in processing relates the movement files to the calibration file and thus the anatomical frame back to the cluster technical frame. This allows the coordinate positions of the anatomical markers to be calculated.

This technique has many advantages over simpler models used in tennis research to date. These can be separated into practical and theoretical advantages. As the anatomical markers are removed for the capture of the movement the player is less restricted by the presence of markers at the joint sites themselves. Additionally, the

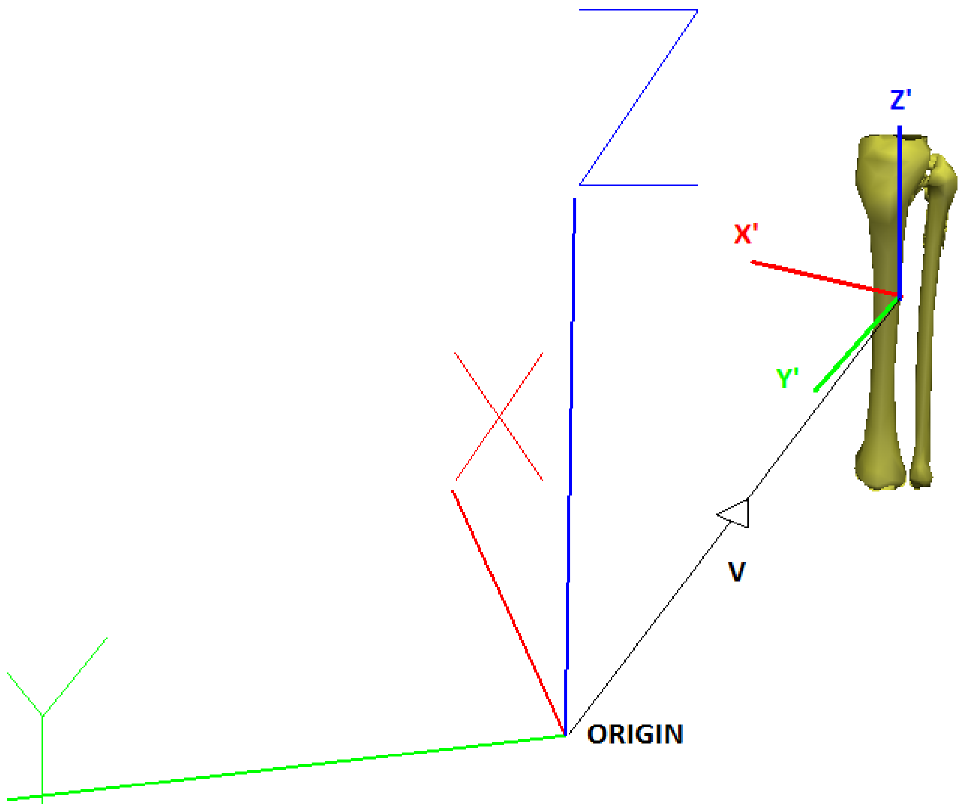


Figure 2.2 - ISB conventions for the global coordinate system and the local coordinate systems of the segments within it. The position of a segment in space is known through the relative position of the segment (local coordinate system) origin and the laboratory origin (global coordinate system) described by the position vector 'V'. The laboratory coordinate system relate to the anterior-posterior (x), medial-lateral (y) and vertical axes, whilst the segment coordinate system refer to the coronal (x), sagittal (y) and longitudinal (z) axes.

clusters can be placed at any part of the segment. The placement of the marker cluster can then be made with consideration for the comfort of the player, the movement that is under analysis, the position of the cameras capturing the movement and where the cluster is least likely to be affected by soft tissue artefact. The configuration of three or more non co-linear markers on a segment used with CAST gives greater scope for measurements outside of the sagittal plane found in the tennis groundstrokes as it allows measurement of all six degrees-of-freedom (Zatsiorsky, 1998). Therefore, the relative positions of adjacent segments can be calculated about each joint axis independently (Richards and Thewlis, 2008). To date, this type of analysis has not been conducted on the tennis groundstrokes. The marker sets used have either been simple (Rogowski *et al.*, 2007), or a customised extension of this approach (Sprigings *et al.*, 1994) that have permitted the calculation of angles in all three dimensions, but not independently.

The limitations of previous approaches have been acknowledged (Gordon and Dapena, 2006), but the measurement of upper extremity motion has suffered from a lack of standardisation in contrast to the lower extremity (Rau *et al.*, 2000), until recently. This lack of standardisation, as evidenced through the different marker set ups described above, may be responsible for the different interpretations of the contributions of body segments to racket velocity apparent in tennis kinematic research to date (Gordon and Dapena, 2006; Lees, 2003). The International Society of Biomechanics (ISB) has presented proposals to standardise the definition of the upper extremity (Wu *et al*., 2005), including the description of anatomical landmarks and the segment coordinate system axes that are derived from them. This development may help to standardise the measurement procedures associated with research into tennis groundstrokes, although difficulties associated with measuring the movement of the trunk (Zatsiorsky, 1998) is a significant obstacle to this.

In summary, the biomechanical analyses of tennis strokes to date are limited by video capture with an insufficient number of cameras, simple marker sets that do not accurately reconstruct the movement at joint sites in all three cardinal planes and a lack of standardisation. This may have led to erroneous judgements in the contributions of particular anatomical rotations to the successful production of these strokes. Measurement using optoelectronic systems, standardised marker sets permitting measurement of six degrees-of-freedom and the use of rigid marker clusters may provide a more optimised solution to quantifying the kinematics of tennis groundstrokes.

2.2 QUANTIFICATION OF THE SPIN OF A TENNIS BALL

Imparting topspin to a ball has been shown to be a useful tactic during tennis rallies. This is due to the difficulty in returning a ball hit with topspin and the decreased chances of making an error through hitting the ball over the baseline. The principles behind these advantages are well explained by Brody *et al.* (2002), and the reader is referred here for further detail of this. Despite these advantages, there are only a limited number of studies that have attempted to quantify the spin of a tennis ball resulting from a tennis stroke. Groppel *et al*. (1983) attempted to predict ball spin from the trajectory and angle of the racket. The predicted values were compared to the calculated ones, and found partial agreement but the method by which the spin was calculated was not provided. Further studies from Stepanek (1988) and Pallis (1997) also provided little detail of the calculation itself or the filming conditions.

Pallis (1997) was first to record the spin of the ball resulting from various strokes played by elite players. He used high-speed video footage recorded at the US Open to establish spin rates up to 3751 rev.min^{-1} for the forehand and 3333 rev.min^{-1} for the backhand for men, and 3488 rev.min^{-1} and 2143 rev.min^{-1} for the women for forehand and backhand, respectively. However, the method by which these were obtained was not presented. Recently, Goodwill *et al*. (2007) and Kelley *et al*. (2008) have recorded ball spin rates during elite match play and a qualifying tournament, respectively. These studies tracked the revolution of the logo on the ball using a high-speed camera(s), with the time for the ball to rotate for one (Kelley *et al*., 2008) or two (Goodwill *et al*., 2007) full revolutions recorded and calculated in rev.min^{-1}. The data recorded during Davis cup matches produced a maximum spin rate of 3800 rev.min^{-1} for the forehand groundstroke (Goodwill *et al*., 2007), whilst the qualifying tournament data recorded a maximum spin rates of 2727 rev.min^{-1} for the backhand and 2857 rev.min^{-1} for the forehand for the competing women (insufficient data was recorded for the men). Neither of these studies was able to ascertain the spin axis of the ball due to the positioning of the cameras, and therefore results relate to ball spin during topspin strokes rather than purely topspin. To the authors' knowledge, only Sakurai *et al*. (2007) have attempted to quantify the spin axis and spin rate of a tennis ball. They attempted this by strategically placing three reflective markers on the ball, and compared three-dimensional spin rates during three types of serve. Unfortunately, owing to the size of the paper, only limited methodology was presented, making it difficult to critique this method. However, the presence of foreign objects on the ball would be likely to affect its properties and hence the spin produced, compared to a ball without markers. Furthermore, as a closed skill it is more likely that a player can hit a serve by hitting the ball directly, and not the markers. However, this would be difficult to achieve when playing groundstrokes and therefore makes this methodology difficult to implement for this type of analysis.

The limited amount of research detailing methodology relating to the collection of the spin of tennis balls highlights the difficulty in accurately quantifying spin. The work of Goodwill *et al*. (2007) and Kelley *et al*. (2008) has focussed on providing data for the ITF from an on-court environment, therefore the accuracy of the set up may be improved under laboratory conditions. Until three-dimensional optoelectronic systems are developed to the stage where markers are not required it appears that high-speed video provides the best solution for tracking ball spin, if the aim is not to alter the natural characteristics of the ball. It should be possible to improve on the accuracy of existing techniques in a laboratory environment, given that existing analyses have been derived from data collected in the field.

2.3 KINEMATICS OF TENNIS GROUNDSTROKES

There are numerous investigations of the key features of tennis groundstrokes dating back to the 19^{th} century. Such work established key features of a variety of tennis strokes. However, the development of the complex modern tennis strokes in the wake of lighter and larger carbon-fibre rackets during the 1980's makes an analysis of much of the research prior to this period irrelevant to this study. It is important that coaches have a scientific basis for the technique they are coaching so that they can be confident their player will have success. New variations of a number of tennis strokes recently suggest that some of the conclusions of previous work may no longer be applicable to the modern game. Furthermore, motion analysis technology has only recently developed to the extent that it is capable of analysing these more three-dimensional strokes. Therefore, this review will focus on more recent analyses dating from 1987 onwards. For a historical perspective of the research into tennis kinematics the reader is referred to Groppel's (1986) review of the biomechanics of tennis.

2.3.1 FOREHAND

The modern forehand stroke is generally more complex, and involves greater rotation of all body segments than the classic style observed thirty years ago (Crespo and Higueras, 2001). Much of the research into the forehand stroke over the last twenty years has attempted to respond to this by establishing key features of various forehands using three-dimensional techniques.

Elliott *et al*. (1989a) highlighted the differences between the more traditional single-unit stroke, commonly observed prior to the development of modern tennis rackets, and the newer multi-segment stroke in the context of proximal-to-distal sequencing of body segments to achieve maximum end-point velocity. The multi-segment stroke produced higher racket velocity at impact (34.5 $m.s^{-1}$) than the single-unit stroke (32.3 $m.s^{-1}$). A single-unit stroke involves the player moving their upper limb almost as one segment throughout the stroke whereas the multi-segment stroke is characterised by a larger amount of elbow ROM in the sagittal plane, therefore requiring the upper arm and forearm to move relative to each other. The multi-segment stroke is initiated with a pivot of the back foot followed by a synchronous shoulder rotation and posterior and upward movement of the elbow. The backswing is then completed by external rotation of the humerus so that the forearm and racket pivot about the elbow and shoulder so that the racket finishes above the elbow and shoulder (Figure 2.3) (Elliott *et al*., 1989a).

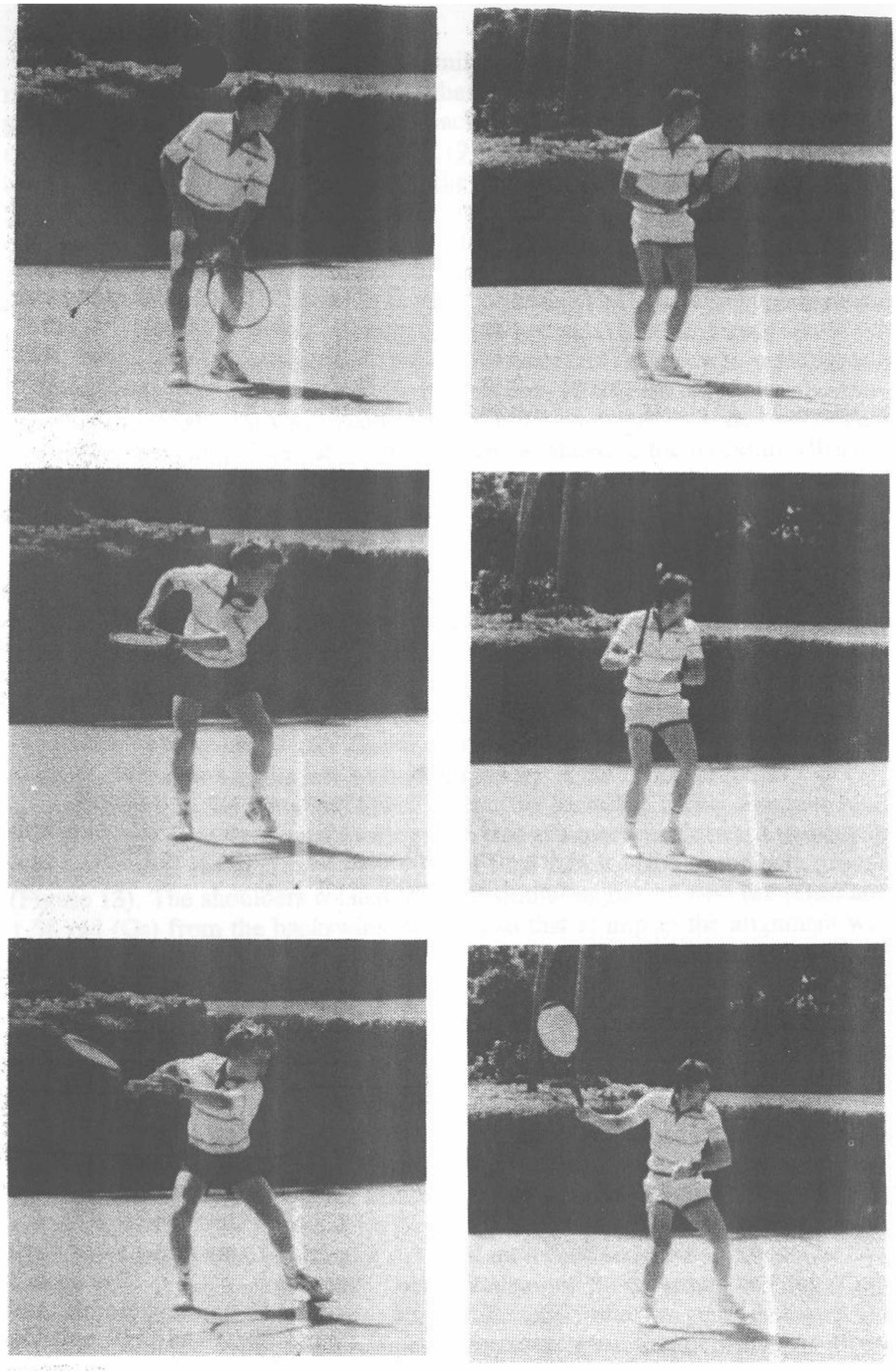
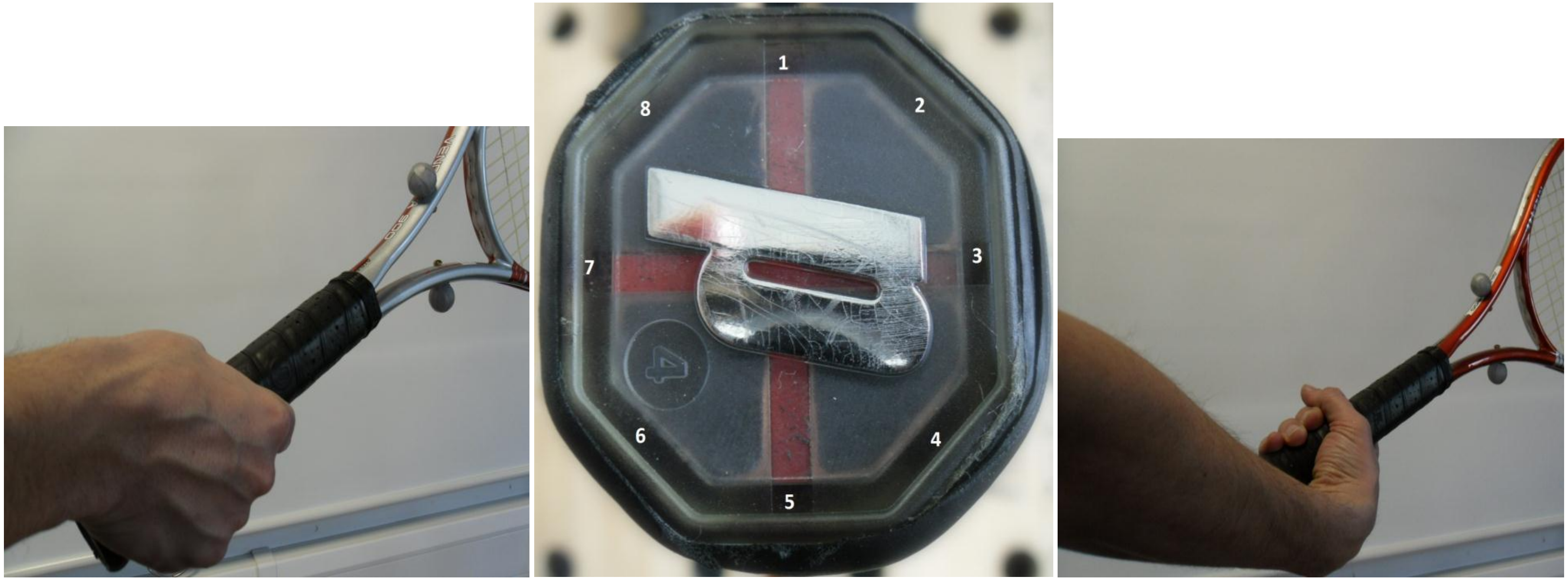


Figure 2.3 – The backswing of the multi-segment (left) and single-unit (right) forehand techniques. (Reproduced from Elliott *et al*., 1989a).

In contrast, the single-unit group rotated the racket about the shoulder simultaneously. This produces a distinct contrast between the backswings of the two different techniques (Figure 2.3). The relative complexities of the two types of forehand in the backswing then govern the complexity in the forward swing. In the single-unit technique the players swing the racket forward using anterior rotation of the upper arm at the shoulder joint. In contrast, the forward swing of the multi-segment technique was characterised by a much larger elbow extension, which in turn produced larger extension and flexion (immediately prior to impact) velocities. There are likely to be a number of reasons why the multi-segment technique produces higher racket-head velocity. One is the more compact position at the completion of the backswing (Figure 2.3). This compact position gives the player a reduced moment of inertia at the beginning of the forward swing and could therefore allow an increase in the velocity of the proximal segments. Increased velocity in the proximal segments could then be transferred to the racket-head distally in the kinematic chain. Similarly, the moments of inertia of the upper arm in relation to the trunk and the forearm in relation to the shoulder are also decreased in the multi-segment technique.

This type of segmental analysis in relation to maximum end-point velocity has been a common method of analysis in recent research into tennis kinematics. Takahashi *et al*. (1996) compared the segmental contributions to end-point velocity across flat, topspin and topspin lob shots. In that regard, their study, and the following analysis incorporating grip position (Elliott *et al*., 1997), represents the best attempts thus far to define the characteristics of topspin strokes in relation to the flatter delivery. Furthermore, whilst the marker set did not permit measurement of all 6 degrees-of-freedom, additional markers were placed at joint sites to better estimate the magnitude of rotations. The upward velocity of the racket increased over the three strokes, with the topspin lob stroke characterised by a higher upward velocity, and a lower forward velocity of the racket. Moreover, the racket was in a closed position for the topspin strokes compared to the flat stroke. This supported the contention of Brody *et al*. (2002) that racket trajectory and velocity are important factors for producing topspin. Various rotations of the upper limb were found to contribute evenly to the development of racket-head velocity, based on the algorithm of Sprigings *et al*. (1994). These results indicate that differing racket positioning and velocity will produce varying amounts of ball spin, but it is not clear which upper limb rotations are important to develop the racket kinematics conducive to high amounts of topspin. Similar trends were found in an extension of Takahashi *et al*.'*s* (1996) work investigating the influence of grip on segmental contribution using the same three forehand strokes (Elliott *et al*., 1997). However, whilst the differences between the strokes were similar to the Takahashi *et al*. (1996) study, it was demonstrated that some differences were apparent for two methods of gripping the racket. The two grips compared were the more traditional 'eastern' grip, where the base of the index finger is placed behind the racket (Figure 2.4A), and the western grip where the base of the index finger is placed underneath the racket (Figure 2.4B). The contributions of the upper limb segments to the upward velocity of the racket were generally greater for the players using a western grip. An upward trajectory, along with the angle of the racket, has been linked to the development of topspin (Groppel *et al*., 1983; Knudson, 1991). Knudson (1991) provided guidelines for the production of topspin stating that upward racket trajectories of 28° to the horizontal, a near vertical racket face at impact, and upward motion of the lower and upper extremity from a square stance were critical features of successful production of the topspin forehand. However, much of the basis of these conclusions were drawn from work prior to the widespread use of the multi-segment stroke characterised by Elliott *et al*. (1989a), and therefore must be interpreted with caution in relation to the modern tennis forehand. Similarly, the inputs into an equation for the prediction of topspin (Groppel *et al*., 1983) were based on older techniques, and the complexity of modern strokes may provide a change in these principles. A particular grip may not be more or less suitable for producing topspin, but will alter the upper limb kinematics.



A) B)

Figure 2.4 – Forehand racket grips. Butt of a racket handle (middle image), Position 1 represents the top of the handle, with position 5 at the bottom. Position 3 is the back of the handle for a right-handed player playing a forehand, with position 7 at the front. A) Eastern grip with the base of the index finger at position 3. B) Western grip with the base of the index finger at position 5.

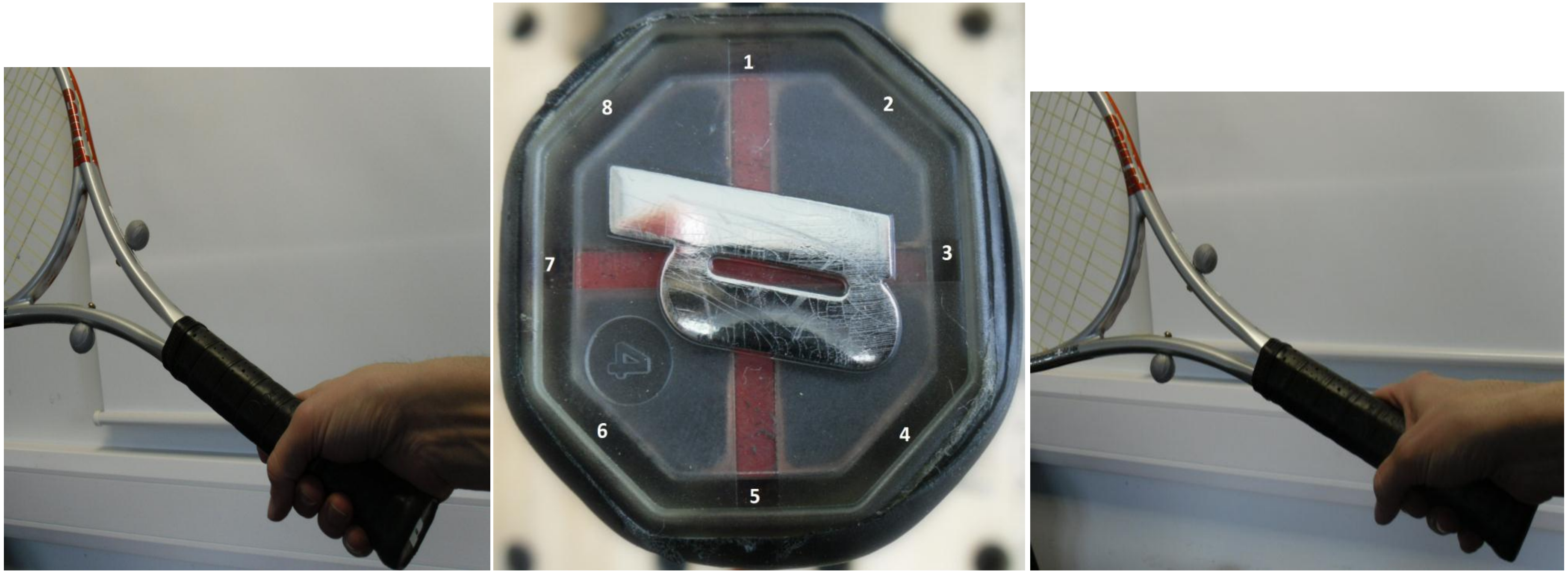
Much of the work of Elliott and co-workers (1995, 1996, 1997) has focussed on the contribution of upper limb segments to racket-head velocity at racket-ball impact. Whilst these segments may be crucial to the generation of racket velocity prior to the impact phase of the stroke, Iino and Kojima (2003) demonstrated that the action of the lower limbs should not be discounted in developing the effectiveness of segments towards the distal end of the kinematic chain. They identified the importance of knee flexion and extension in rotating the trunk whilst striking a forehand. When players were asked to restrict the motion at the knee joint, there was a reduction in flexion and internal rotation of the hip and pelvic torque compared to an unrestricted shot. The outcome of this restriction was a reduction in racket-head velocity at racket-ball impact (25.9 $m.s^{-1}$ restricted shot, 28.2 $m.s^{-1}$ unrestricted shot). It may be stated that placing restrictions on a player's natural game may automatically lead to a decrease in performance, therefore possibly overstating the role of lower limb flexion. However, this work does highlight that the lower limbs play a part in the kinetic chain, and that is an area worth investigating for future research.

While the role of knee flexion may be important, the stance from which it is played may be less so. Knudson and Bahamonde (1999) compared the kinematics of two stances, the modern open stance with the position of both feet pointing at the net, and the more traditional square stance where the toes point perpendicularly to the net. They found only small differences in racket kinematics between the two stances. There was a non-significant increase in racket velocity in the square stance, linked by the authors to a greater rotation of the trunk, but the sequencing of segments in the strokes remained the same along with the path of the racket. With an increase in the prevalence of the topspin stroke, combined with the popularity of the open-stance stroke it is tempting to assume that this stance may provide a basis for greater topspin production, contrarily to Knudson (1991). However, no link between the stance and the production of ball spin has been established.

Research into the kinematics of the tennis forehand stroke has investigated the key features of the modern stroke through three-dimensional analysis. However, while much of the methodology does not allow the full range of planar motion to be measured some of the values obtained may be questioned. The work of Takahashi *et* *al*. (1996) has identified some racket kinematics that might be important in producing topspin, in terms of the contributions of segments to racket-head velocity for topspin strokes. However, as Elliott (2006) states, the contributions of anatomical rotations to velocity do not necessarily indicate the importance of a movement to a particular stroke. Thus, the true value of an anatomical movement or position to topspin can only be established in relation to the amount of spin produced. At the present time no study has confirmed which aspects of forehand technique are responsible for the generation of high ball spin rates. The concurrent measurement of ball spin and three-dimensional analysis of groundstrokes using modelling techniques that allow measurement in six degrees-of-freedom are crucial for the mechanisms behind topspin generation to be understood.

2.3.2 BACKHAND

The backhand groundstroke has received relatively little attention in comparison to the forehand. Recent work has compared the increasingly popular double-handed stroke with the more traditional single-handed stroke across kinematics (Kawasaki *et al*., 2005) and kinetics (Akutagawa and Kojima, 2005). The backhand has also been investigated with regard to the causation of lateral epicondylitis (tennis elbow) (Blackwell and Cole, 1994; Knudson and Blackwell, 1997). Both of these studies highlighted that a flexed position at racket-ball impact is a potentially causative factor, with Blackwell and Cole (1994) presenting electromyography data showing low wrist extensor activation in novice players as a reason for this flexed wrist position. Less is known regarding the anatomical rotations that influence the successful production of the stroke. Despite the interest in the one- and two-handed grips, there have not been any studies analysing grip related to specific positioning on the racket as Takahashi *et al*. (1996) and Elliott *et al*. (1997) did for the forehand. This may be due to the number of variations of grip. There are two basic backhand grips; the continental and the eastern (Knudson, 2006) (Figure 2.5), but there is also the addition of a non-dominant hand in a number of positions in the case of the double-handed grip.



A) B)

Figure 2.5 – Backhand racket grips. Butt of a racket handle. Position 1 represents the top of the handle, with position 5 at the bottom. Position 3 is the front of the handle for a right-handed player playing a backhand, with position 7 at the back. A) Continental grip with the base of the index finger at position 2. B) Eastern grip with the base of the index finger at position 1. The non-dominant hand often supports the racket underneath the grip at approximately bevel 6 for the double-handed technique.

As with the forehand, the first significant three-dimensional analysis was undertaken by Elliott *et al*. (1989b). They compared three types of topspin backhand, two of which were stationary shots and the other a running shot down the line. The two stationary shots were either played down the line or across court. A common feature of the three strokes was an upward trajectory of the racket throughout the forward swing through to racket-ball impact. This supports the contention of Brody *et al*. (2002), that the trajectory of the racket is important when playing topspin strokes. The kinematics of the upper limb were relatively consistent across the three types of stroke, but with a difference in shoulder alignment at ball impact when playing across court and an adjustment in trunk position when playing on the run. Interestingly, all players in this study used a single-handed backhand grip, something that is becoming less familiar in modern tennis. As this study only compared topspin strokes it is not possible to ascertain, the kinematic differences between these and flat deliveries.

A later study (Reid and Elliott, 2002) investigated the flat and topspin backhand strokes in the context of the single- and double-handed grips. They made a comparison of down-the-line and across-court strokes played with a flat delivery and the topspin lob down-the-line stroke with each grip. The kinematics of the double-handed grip strokes could be characterised as having a lesser ROM, with significantly lower shoulder and hip rotation found irrespective of the stroke played, a similar pattern was also identified by Kawasaki *et al*. (2005). The sequencing of body segment rotations remained similar for both types of grip, although some players used greater levels of elbow flexion-extension than others when using the double-handed technique. Surprisingly, there were no differences across the strokes in terms of the human kinematics, but there were effects for the racket kinematics. The authors defined an angle termed ‘racquet topspin’, which was defined as the angular displacement of the axis running from the throat to the tip of the racket with respect to the vertical. Due to the limited number of cameras this was only recorded at the end of the backswing phase and at impact, but did give an insight into the trajectory of the racket throughout the forward swing. At the end of backswing no significant effects were found across the three strokes, but there was a clear difference between the double- and single-handed techniques. The single-handed technique started from a position above the horizontal, whilst the double-handed technique started from a position below the horizontal. Furthermore, there was a lower starting position of the racket within the double-handed group for the topspin down the line stroke compared to the other two. These differences may relate to a more upward racket trajectory for the double-handed topspin lob down the line stroke through the forward swing if the height in which the ball is struck remains consistent across all strokes. The similar angles at impact across all strokes indicated this was the case. These results may indicate that a double-handed technique could be more effective in producing topspin. However, as the trajectory of the racket could not be calculated throughout the forward swing and ball spin was not measured this can only be speculated upon.

Thus far, differences between the one- and two-handed backhand techniques have been explored in relation to movement and ultimately end-point velocity. The consensus is that each stroke has its merits in producing maximum racket velocity at impact with the ball (Reid and Elliott, 2002). Whether either technique has any advantages in relation to the production of topspin is not yet known. The racket kinematics resulting from the two-handed technique (Reid and Elliott, 2002) may indicate an advantage from this technique in producing topspin. However, the motion of the racket and the anatomical rotations must be analysed throughout the forward swing of the stroke for this to be established. This must also be carried out simultaneous to the ball spin produced as a result of these strokes. However, to date, no studies have measured the spin of the ball and the kinematics of the player concurrently. This represents a gap in the scientific knowledge that coaches might draw upon when informing their coaching practice of the backhand topspin stroke.

2.4 USE OF SCIENTIFIC EVIDENCE IN COACHING PRACTICE RELATED TO TOPSPIN GROUNDSTROKES

Researchers investigating tennis strokes have sought to make their investigations relevant to players and coaches. As a result, a number of publications have aimed to summarise the key findings of scientific research in the context and language to be of practicable use to the coach. The overwhelming focus of these summaries is on the production of power in the various strokes (Elliott, 1995; Crespo *et al.*, 2000), with the production of spin receiving less attention. Indeed, Crespo *et al*. (2000) emphasise the importance of topspin and backspin but do not explain how it might be produced.

In the last ten years, coaching literature has focussed more on topspin production, reflecting the changing nature of the game. Bahamonde (2001) discussed the emergence of the topspin forehand during the previous decade. He advised that a western (Figure 2.4) or semi-western forehand grip was best for generating topspin and that the stroke arc and racket inclination at impact were key elements of the topspin forehand. These factors were discussed at length in scientific books designed to appeal to coaches and players (Cross and Lindsey, 2005; Knudson, 2006). Each of these texts discusses the effect of topspin on ball flight and the reduction of errors associated with hitting the ball out of the court. They go on to explain how the stroke arc can produce topspin. Knudson (2006) explains that hitting topspin strokes requires the spin direction to be reversed and that high racket speeds and a steep racket trajectory through impact is required. He provides specific guidelines of a racket path 35-50° to the horizontal and a racket-head alignment 5° to the vertical at ball impact. Cross and Lindsey (2005) explain that it is the combination of these factors that determines the relative angle of the racket-head and the ball at impact. It is this angle, the relative speeds of the racket and ball and the inbound spin rate of the ball that determine the ball spin rate following impact (Cross and Lindsey, 2005). Whilst these books may have provided the best insight into spin production to date, neither expanded on which human joint rotations or sequences might achieve the desired racket kinematics at impact.

With the paucity of specific information regarding topspin production from tennis groundstrokes it is not surprising that many coaching texts reflect the scientific understanding to date. Bollettieri's (2001) coaching manual predominantly focuses on the generation of power from racket-head velocity in a number of strokes. Whilst texts such as Brown (2004) and Antoun (2007) acknowledge the importance of topspin but do not refer to how it might be generated. The clearest advice on topspin production is the repetition of Cross and Lindsey's (2005) recommendation to brush the racket up the back of the ball.

There appears to be a need for clearer information from the scientific community on how topspin may best be produced from tennis strokes, so that coaches can base guidelines to players from a solid evidence base. It would be useful to know which techniques, or specific anatomical rotations were responsible for producing high amounts of topspin for the forehand and backhand strokes.

2.5 AIMS AND OBJECTIVES

The aim of this investigation is to determine which kinematic variables, or combination of variables, produce the highest amount of topspin in tennis groundstrokes. To achieve this, a number of objectives must be fulfilled.

- To quantify the full movement of each joint rotation related to the tennis groundstrokes in the sagittal, coronal and transverse planes.

- The development of a method to quantify ball spin resulting from tennis groundstrokes using high-speed video.

- To establish the kinematic differences between flat and topspin tennis groundstrokes.

- To determine the relationship between the kinematic variables associated with tennis groundstrokes and the amount of topspin generated.

- To present information in a manner suitable to disseminate to tennis coaches and professionals seeking to develop their game.

3. DEVELOPMENT OF METHODS

Following a feasibility study, a number of issues were identified as of paramount importance in order to accurately quantify joint motion in the sagittal, coronal and transverse planes and the determination of the spin rate of the tennis ball. This chapter describes these key issues and the investigations undertaken in order to optimise the quantification of joint motion in each cardinal plane and to determine the spin of the tennis ball prior to the main investigation.

3.1 CLUSTER DESIGN AND PLACEMENT

3.1.1 INTRODUCTION

Observation of pilot testing revealed that the rigid clusters of markers used were ill-equipped to accurately measure the movement of the underlying bones in the upper limb segments, particularly in axial rotation. This was particularly true of the junior players in the cohort, owing to the relative size of the clusters to the underlying bone. These are known as marker- (Cappozzo *et al*., 1997) or anatomical-clusters (Cappozzo *et al*., 2005), and their representation with respect to the underlying bone is most accurate when they are optimally designed. Cappozzo *et al*. (1997) produced parameters by which marker clusters best represent the underlying bone. These considerations include the number of markers in a cluster (practical solution of 4), the relative position of the markers in terms of the geometry, size and shape of the cluster and the position and orientation of the cluster in relation to anatomical landmarks. Considering these guidelines will allow close approximation of the underlying bone and provide more accurate representations of longitudinal rotations of body segments.

The use of rigid clusters allows the experimenter to place the cluster on a position on the segment that will minimise the movement of soft tissues with respect to the underlying bone. However, if the experimenter is interested in measuring the axial rotation of the forearm then this option is not available. The forearm segment is unique, in that, the axial rotation is produced as a result of the motion of the radius and ulna not a single bone, as is the case with the humerus or femur. As the radius and ulna are relatively fixed at proximal and distal ends there is limited axial rotation of them independently, and the anatomy is such that there is greatest axial rotation of the forearm at the distal end of the segment. Therefore, a marker cluster must be placed at the distal end of the forearm if the entire ROM of axial rotation is to be measured. This places a further constraint on the size of the cluster, in part due to the distal end having the smallest circumference, but mainly as the amount of rotation varies throughout the segment and the cluster must be small enough about its long axis to measure only at the distal end. Therefore, some of the freedoms in designing clusters proposed by Cappozzo *et al*. (1997) are removed in the case of the forearm.

The primary aim was to assess a variety of designs of rigid clusters in their ability to measure the axial rotation of the forearm through a pre-determined ROM. A secondary aim was to quantify the relative positions of the forearm and humerus segments in three-dimensional space, and the resulting elbow kinematics as a result of different placements of the rigid clusters. The secondary aim was as a result of observations of an animation whereby the elbow joint appeared 'dislocated' in some phases of movement when distal cluster positions were used for these segments.

3.1.2 METHODS

The two aims were assessed based on different methodologies and will be presented in turn.

3.1.2.1 AIM 1 – ASSESSMENT OF CLUSTER DESIGNS ABILITY TO MEASURE AXIAL ROTATION

Anthropometric data was collected from a cohort of ten junior tennis players, specifically the length and girth of the upper and lower limb segments. This enabled marker clusters to be designed to better fit the segment morphology of the players than the clusters used in the pilot tests. The observed ranges of the anthropometric measures appeared sufficiently small to manufacture a single set of clusters, thereby adopting a one size fits all approach. Potential limitations of this approach were most likely to be observed with the forearm cluster, due to the specific placement of the cluster required in order to measure axial rotation. The measured length of the forearm from the lateral epicondyle of the humerus to the styloid process of radius and ulna ranged from 200-250 mm, whilst the girth of the forearm at the distal end ranged from 102-144 mm. The marker clusters were designed to accommodate the upper end of the forearm girth, with the assumption that this would still provide a reasonable coupling for players at the lower end of the ranges reported. Three designs of the rigid clusters were manufactured to reflect the properties as recommended by Cappozzo *et al*. (1997). Therefore, the longitudinal axis of the cluster was designed as the longest section, there were four markers for each design, and each design distributed the markers in three dimensions.

Some of the designs incorporated stems, the purpose of which is to make them more visible to the cameras tracking them and to add a greater contrast in terms of three-dimensionality. The potential disadvantage of these designs was movement of the markers in relation to the others on the cluster due to the stem itself, therefore care was taken to make these sufficiently thick. The three new designs were termed based on the length of stems, or a mixture of short and long and were termed ‘short-stem’, long-stem’, ‘3D’ (Figure 3.1). A further cluster representing a more common design was used for comparison, termed ‘original’.

The effectiveness of each cluster design in measuring a 90° axial rotation was assessed using a method previously used to assess the use of a simple cluster design (Protheroe *et al*., 2006, Appendix A). Five participants rotated a goniometer through 90° by means of axial rotation of the forearm. This was achieved using a device that coupled the goniometer to the wrist (Figure 3.2). The participant sat at a table with their forearm resting on it in a fully internally rotated position. This was set as ‘zero’. The elbow remained flexed at an approximate orientation of 90° to isolate the rotation of the forearm from that of the humerus. The participant rotated the forearm in supination whilst maintaining a stationary elbow position throughout. A small cushion was placed at the elbow to limit the movement of the upper arm, however it was likely that some movement of the upper some was still permitted. If excessive movement of the trunk, or upper arm were observed using the motion capture software then the relevant trial was discarded. Rotations for each design of cluster were performed at three speeds, a duration of 8 seconds to complete the movement, 2 seconds, and as fast as the participant could manage. The fastest condition would typically be completed in approximately 0.5 seconds. This is more representative of the speed of rotation expected in a tennis stroke. Each condition was repeated five times for each cluster, of which there were four.

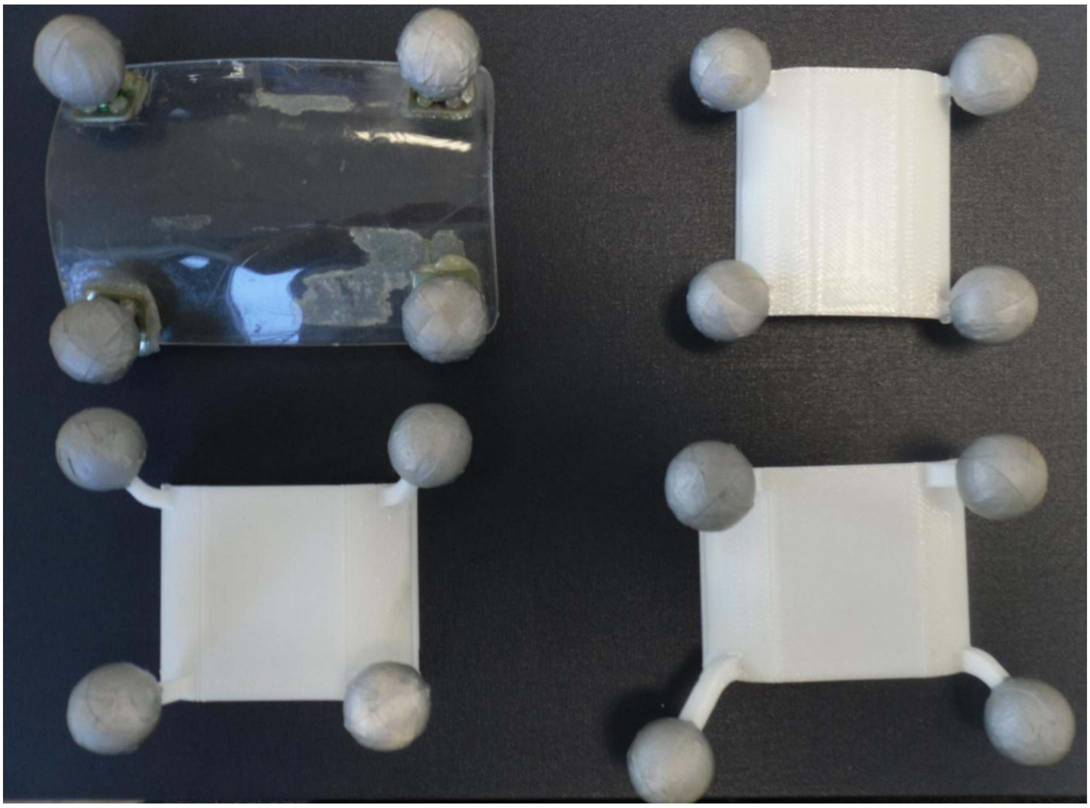


Figure 3.1 – Rigid clusters designed for placement at the distal end of the forearm segment. Clockwise from the top left are the original, short-stem, 3D and long-stem clusters.

The movement was captured using a seven camera motion capture system (Qualisys AB Medical Sweden) operating at 240 Hz. The rotation of the forearm was determined relative to the stationary humerus using the different designs of rigid clusters of four non-collinear markers. The various forearm clusters were placed at the most distal point possible. The forearm was defined proximally by the medial and lateral epicondyles of the humerus and distally by the styloids of the radius and ulna whilst the humerus was defined proximally from a point 0.055 m inferior to the acromion process of the scapula, similar to the method of Schmidt *et al*. (1999) who used a value of 0.07 m, and distally by the medial and lateral epicondyles of the humerus. As the method of locating the shoulder joint centre is based on a measured distance, this may introduce error into the calculation of shoulder kinematics. Therefore, these results should be interpreted with some caution. Axial rotation was determined by the third rotation in the XYZ Cardan sequence using movement analysis software (Visual 3D; C-motion, USA). The cluster consistently permitting 90° of axial rotation to be recorded at each speed was chosen as the ideal design.

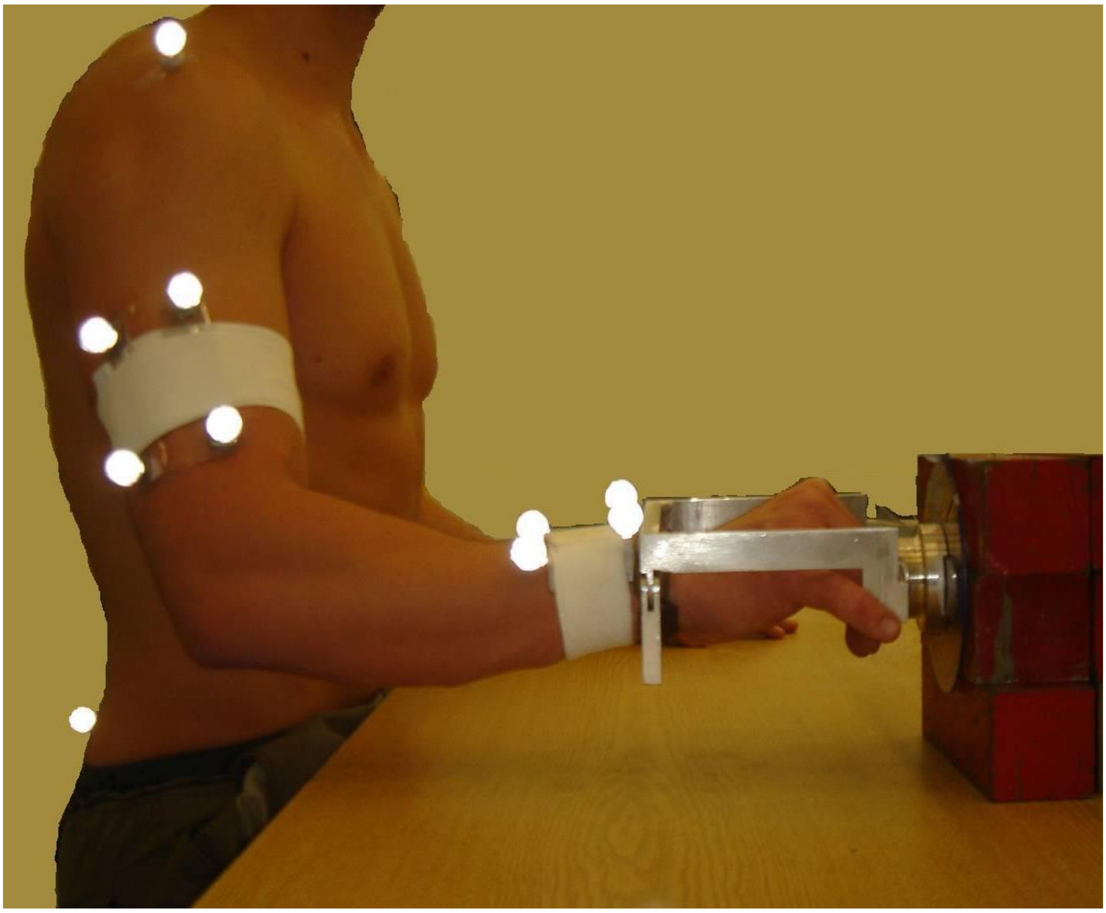


Figure 3.2 – The forearm rotation device coupling the goniometer to the wrist.

3.1.2.2 AIM 2 – DETERMINATION OF OPTIMAL CLUSTER POSITIONING

The forearm and humerus segments were constructed as for the previous methods, with the exception that the humerus was defined at the proximal end based on a functional movement calculated using the method of Schwartz and Rozumalski (2005). The participant was instructed to maximise the ROM of the upper limb, whilst keeping the position of the shoulder itself fixed, thus preventing elevation or protraction or retraction of the scapula. In practice, this required the participant to maintain the upper limb relatively adjacent to the trunk, making small circular movements with the upper limb. The movement was recorded for 10 seconds, equating to 2400 frames of data to input into the algorithm. If significant movement of the marker on the acromion process of the scapula was observed using the motion capture software then the functional movement was recaptured. Two marker clusters, each consisting of four markers matching the short-stem design (Figure 3.1), were placed on each segment. One placed at the proximal end and one at the distal end.

One participant performed ten forehand tennis groundstrokes. The marker data was captured using a nine camera motion analysis system (Qualisys AB Medical, Sweden) at 240 Hz.

The apparent ‘dislocation’ of the elbow joint was assessed by plotting the position of the distal end of the humerus with the proximal end of the forearm in each cardinal plane. Elbow kinematics were calculated using the Cardan sequence ‘XYZ’, corresponding to ordered anatomical movements in the sagittal, coronal and transverse planes. The Y axis was chosen for analysis due to its limited, but known ROM. The motion is a combination of abduction of the elbow and the carrying angle between the upper arm and forearm. A total of four models were constructed that referenced the anatomical reference frames to the various positions of the rigid clusters of markers. Thus, kinematics were calculated based on a distal forearm cluster and a distal humeral cluster, a distal forearm cluster and a proximal humeral cluster, a proximal forearm cluster and a distal humeral cluster and a proximal forearm cluster and a proximal humeral cluster.

The optimal position of each cluster on the humeral and forearm segments was assessed subjectively based on the congruency of the humeral and forearm segments and the ROM in the coronal plane at the elbow joint. As the full measurement of axial rotation of the forearm may be important in relation to tennis groundstrokes, optimal cluster positioning needed to include a distal forearm cluster position. Nevertheless, each combination of cluster position was considered to assess whether the distal forearm cluster could introduce a source of error into the kinematics calculated at the elbow.

3.1.3 RESULTS

3.1.3.1 AIM 1 – ASSESSMENT OF CLUSTER DESIGNS ABILITY TO MEASURE AXIAL ROTATION

Table 3.1 – Mean (SD) measured range ROM of forearm axial rotation

Cluster	**ROM (°)**		
	8 seconds	2 seconds	Fast
Original	40.70 (1.88)	35.99 (2.96)	44.35 (3.34)
Short-stem	88.60 (1.19)	90.92 (1.58)	93.10 (4.48)
Long-stem	90.40 (2.45)	81.21 (5.57)	94.55 (1.65)
3D	88.78 (2.42)	84.50 (2.96)	89.66 (2.68)

The results presented in Table 3.1 indicate that the three new cluster designs were close to recording the target angular displacement of 90°, but the older cluster design was not accurate in measuring this.

The effect of altering the position of the marker clusters on the relative positions of the forearm and upper arm segments at the elbow are shown in Figure 3.3. Close proximity of the two traces on each graph indicates that distal end of the humerus segment and the proximal end of the forearm are in a similar position in space. The effects of these differences on elbow kinematics are shown in Figure 3.4.

3.1.3.2 AIM 2 - DETERMINATION OF OPTIMAL CLUSTER POSITIONING

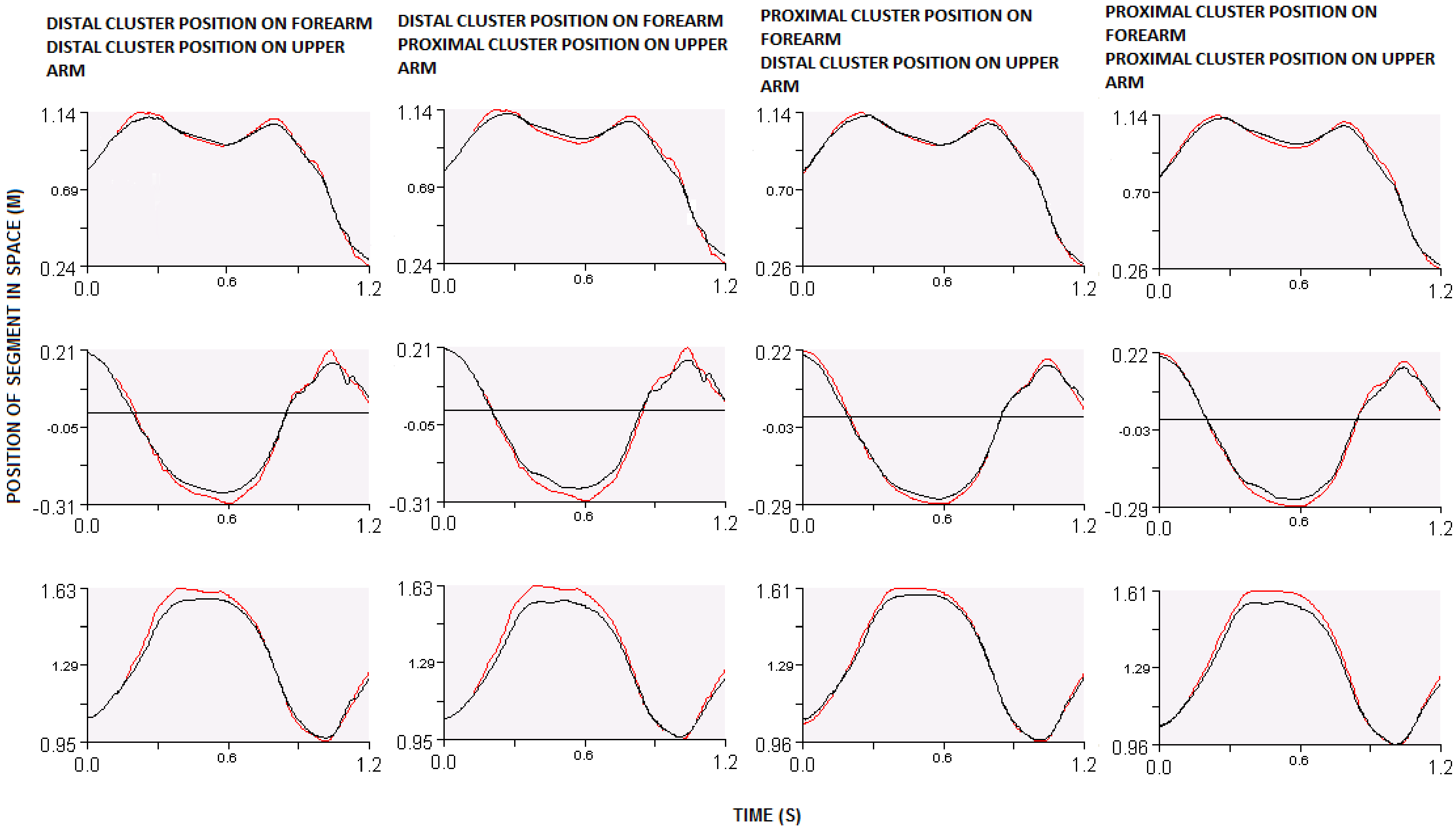


Figure 3.3 – Relative positions in space between the proximal end-point of the forearm segment (red trace) and the distal end-point of the upper arm segment (black trace) in *x* (top), *y* (middle) and *z* (bottom) lab axes. Close proximity of the traces on each graph indicates close proximity between the two segments at the elbow joint.

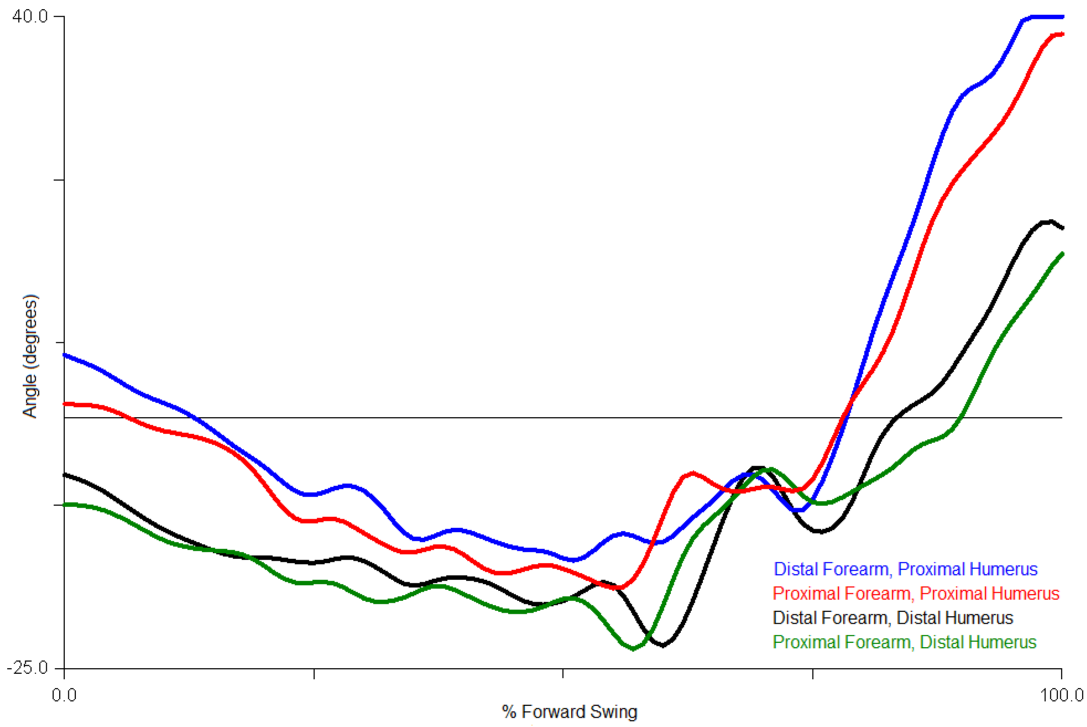


Figure 3.4 – The effect of changing the position of marker clusters on a segment on elbow kinematics about the y-axis, an axis known to have limited ROM. The black trace represents distal positioning of forearm and humeral clusters, the red trace represents a proximal position on the segment for each cluster. The blue trace represents a distal position for the forearm cluster, but a proximal position of the humeral cluster. The green trace represents a proximal positioning of the forearm cluster and a distal position of the humeral cluster.

3.1.4 DISCUSSION AND CONCLUSIONS

The three new cluster designs were all shown to measure axial rotation to within 10° over a total of 25 trials for each cluster at various speeds (Table 3.1). Given some error derived from the coupling between the forearm and goniometer, the actual ROM may not have equalled 90° in each trial. Therefore, the errors associated with each cluster may not have been as large as 10°. Nevertheless, this still represents a significant error of the magnitude reported by Leardini *et al*. (2005) in their survey of errors associated with soft tissue artefact (STA). Therefore caution should be exercised in interpreting small differences in this movement in a sporting or clinical situation.

The original cluster was representative of a large rigid plate, not custom-designed for the segment and placed slightly away from the distal end-point. The results for this cluster highlight the importance of good cluster design in order to measure axial rotation. Each new design showed a level of accuracy within 2° when the movement was completed within 8 seconds, but the overall accuracy dropped with increasing speed. This may be an indication that the definition of the upper limb segments and the angle decomposition method are reasonably accurate, but that STA plays a greater role with increasing speed. This explanation would support the contention of Leardini *et al*. (2005) that STA is velocity-dependent.

Of the three new clusters tested, there was no clear pattern as different clusters appeared to perform better at different speeds. However, the short-stem design was the only cluster with a mean error within 3.5° of the target value of 90° for each condition (Table 3.1). This design was considered a planar design, and therefore not ideal on the basis of Cappozzo *et al*. (1997) guidelines, but this would have ensured that the longest principle axis of the marker cluster coincided, or was close to, the longitudinal anatomical axis of the forearm. The short-stem design also has the practical advantage that it would be less likely to be broken through collision with another body segment.

Altering the position of the forearm and upper arm segment marker clusters affected the global positions of the segments in three-dimensional space and the resulting elbow kinematics. Figure 3.3 indicates that the proximity of the forearm and upper arm segments are more congruent when the forearm cluster is at a proximal position on the segment and the upper arm cluster is at a distal position. This is not surprising due to the proximity of the two marker clusters, nor does it account for the accuracy of the segments at the opposing ends. The other combinations of cluster position appear to provide similar discrepancies in each axis. The effect of the cluster positioning on the elbow kinematics about the y-axis is illustrated in Figure 3.4, and shows that no configuration is without error. Due to the anatomy of the elbow there is limited ROM about the y-axis, however the kinematic calculation of the forearm with respect to the upper arm segment will include the so-called ‘carrying angle’. This is the relative angular position of the upper arm and forearm when viewed in the coronal plane. This angle will take different values depending on the amount of elbow flexion, but is unlikely to exceed 11° (MacWilliams *et al*., 2010). Thus, any motion outside of this range, as viewed in Figure 3.4, can be considered error. Such error could be propagated from smaller errors in anatomical definition from marker misplacement and STA. As the different configurations of cluster position all used the same anatomical frame, the differences in kinematics are solely due to the cluster position and could be attributed to STA. The positioning of the humeral cluster appears to alter the coronal kinematics at the elbow (represented by the red and blue lines – Figure 3.4) to a greater extent than the forearm cluster. In each case there is a large ROM associated with the proximal placement of the humeral cluster. This highlights the challenges of cluster positioning on this segment, particularly avoiding movement due to the contraction of m. biceps brachii. The distal positioning of the upper arm cluster provides similar coronal kinematics with a smaller ROM, regardless of the position of the forearm cluster. Given that altering the position of the forearm cluster has a limited effect on coronal kinematics, evidenced through ROM (Figure 3.4), it makes sense to place this cluster in the distal position whereby the axial ROM can be fully measured.

In summary, the distal placement of each upper limb cluster should enable the full axial rotation ROM of the forearm to be measured, whilst continuing to minimise error about the other axes. This was based on the smaller ROM associated with coronal kinematics at the elbow (MacWilliams *et al*., 2010) that accompanies a distal placement of the humeral cluster whilst allowing the full ROM of the forearm to be measured through a distal placement of the cluster on that segment. It is acknowledged that this configuration of cluster positions does not provide the best solution in terms of the congruency of the adjacent segments at the elbow (Figure 3.3), but in the context of this investigation measuring the axial rotation of the forearm is of paramount importance.

3.2 CALCULATION OF SHOULDER KINEMATICS

3.2.1 INTRODUCTION

The anatomical landmarks and segment constructions have been well defined for lower limb analyses (Cappozzo *et al*., 1995), mainly due to the efforts of those interested in the analysis of human gait. The International Society of Biomechanics (ISB) have attempted to standardise definitions of joint coordinate systems of the upper limb (Wu *et al*., 2005) and the spine (Wu *et al*., 2002), but the challenges to overcome in modelling the upper extremity are numerous. These are well summarised by Rau *et al*. (2000) (Table 3.2).

Table 3.2 – Comparison of gait analysis and upper extremity analysis. (Reproduced from Rau *et al*., 2000).

Gait analysis	Upper extremities
One standard movement	Task-dependant movements
Cyclic	Non-cyclic
Approx. 2D	3D
External forces easily measurable	External forces difficult to assess
Limited ROM	Extremely large ROM
Standard protocols exist	No standard protocols
Ready-to-use systems available	No adapted systems available

The shoulder joint has received the most attention due to its complexity and key role in linking the trunk with the upper extremity. The shoulder complex consists of three joints; the sterno-clavicular, the acromio-clavicular and the gleno-humeral joints (Bao and Willems, 1999). Scapulo-thoracic movement is a result of the combination of movement at the sterno-clavicular and acromio-clavicular joints (Thompson and Floyd, 1998). To date, many investigations (Rab *et al*., 1995, 2002; Wang *et al*., 1998) have examined the humerus in relation to the thorax, thus creating the non-existent thoracohumeral joint (Wu *et al*., 2005). Other approaches include focusing only on the gleno-humeral joint (e.g. Hingtgen *et al*., 2006) and combining the gleno-humeral and acromio-clavicular joints and modelling the sterno-clavicular joint separately (Bao and Willems, 1999).

The ISB has attempted to standardise the measurement of the upper extremity (Wu *et al*., 2005) by providing definitions of body segments, the landmarks that identify them, the coordinate system of each segment and calculation of angles between adjacent segments. The standardisation proposed specific Cardan/Euler angle sequences for each adjacent segment in the upper extremity (Wu *et al*., 2005). However, the ability of the proposed angle sequences to produce anatomically meaningful descriptions of movement at the shoulder was challenged by Šenk and Chèze (2006). The basis of that investigation was that the shoulder is associated with movements with a large ROM and that some movements cannot be described using Euler sequences. More specifically, a large ROM about the first axis is potentially problematic, if the second and third angles are of interest, as Cardan/Euler angles are sequence-dependent and errors are largest in the third rotation (Cappozzo *et al*., 2005). Euler sequences, such as 'YXY' (ZYZ in relation to axes for current study – Figure 3.5) proposed for the gleno-humeral joint and the humerus relative to the trunk, do not account for movement in the axis not considered, elevation in the sagittal plane for the example given. Šenk and Chèze (2006) investigated the effectiveness of a number of Cardan/Euler rotation sequences for a number of movements. The effectiveness of each rotation sequence was judged against the parameters of gimbal lock and whether the calculated angle matched the expected ROM, termed 'amplitude coherence'. Gimbal lock is an indetermination of angles caused when the second rotation equals ± 90° (Hamill and Selbie, 2004), this leads the first and third axes to coincide during the movement (Šenk and Chèze, 2006). Šenk and Chèze (2006) observed that each rotation sequence could be affected by gimbal lock and a lack of amplitude coherence, but that the optimal sequence varied according to the movement performed. Therefore, the implication is that the recommended ISB angle sequence for each joint at the shoulder will not provide anatomically meaningful angles for every type of movement.

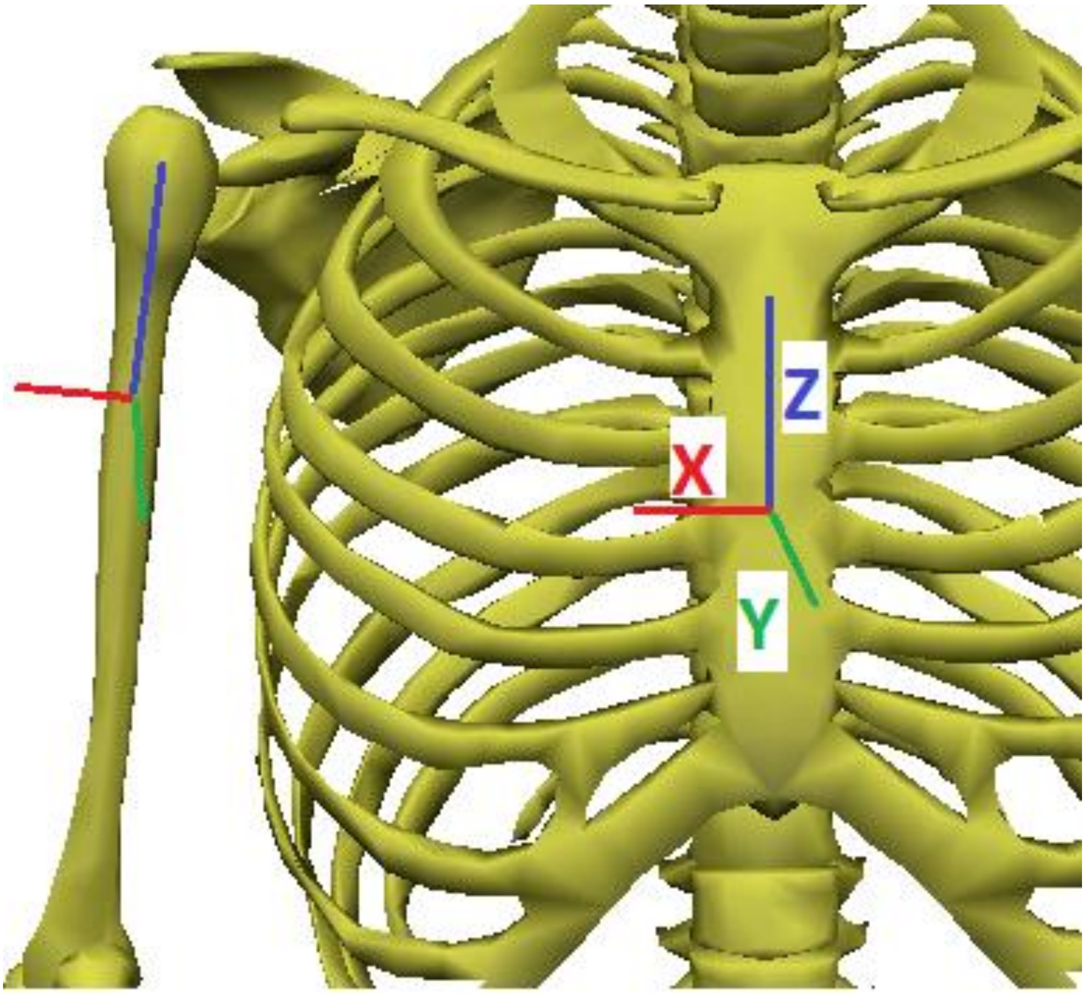


Figure 3.5 – Coordinate system describing the trunk and humerus segments. Anatomically the blue axis (Z) represents the longitudinal axis permitting movement in the transverse plane, the green axis (Y) represents the anterior-posterior axis permitting movement in the coronal plane and the red axis (X) is orthogonal to the other two permitting sagittal plane movement.

Not only is movement at the gleno-humeral joint difficult to quantify, but there are also different methods of defining the gleno-humeral joint centre. It is important to define the proximal end point of the humerus in order to quantify movement at the gleno-humeral joint and the axial rotation of the humerus, however, the joint centre is not a bony landmark (Wu *et al*, 2005). The preferred method of the ISB is to calculate the centre of rotation through a functional movement that calculates the pivot point of the humerus in relation to the adjacent segment at the shoulder (Wu *et al.*, 2005). However, regression methods also exist that calculate the joint centre from an inferior offset from a marker on the acromion process of the scapula. These offsets have been calculated from regression based on the distance between the left and right acromion processes (Rab *et al*., 2002; Hingtgen *et al*., 2006), or simply from a measured distance from the acromion process to the palpated joint centre (Schmidt *et al*., 1999). As Wu *et al*. (2005) acknowledge, functional methods may not be suitable for all studies depending on the capabilities of the participants but questions remain on the relative merits of the two approaches. Elliott and co-workers (1995, 1996, 1997) adopted a further approach, whereby markers were placed on the anterior and posterior aspects of the palpated head of the humerus, with the joint centre defined as the mid-point of these markers. This technique is heavily reliant on the investigators ability to accurately palpate a landmark with a large surface area without easily identifiable features. Large errors in angle calculation can propagate from potential misplacements when movement is considered in multiple planes of motion (Della Croce *et al*., 2005).

Clearly, several issues remain unresolved and there is likely to be further response yet to the ISB proposals from other researchers interested in shoulder kinematics. An improvement on the modelling of the shoulder joint and description of angles used in research into tennis groundstrokes thus far is likely to yield a more accurate representation of internal rotation of the upper arm. This movement has been identified as critical to the generation of racket velocity in tennis strokes (Marshall and Elliott, 2000), and may also be an important factor in ball spin production. The aims of this investigation were to assess the differences in shoulder kinematics as a result of two definitions of the proximal head of the humerus and to investigate the effect of a variety of Cardan / Euler sequences on the calculated kinematics of a number of movements at the shoulder, in particular whether the ISB recommendation for the gleno-humeral joint was suitable for tennis groundstrokes.

3.2.2 METHODS

The shoulder joint was modelled as the relative position of the humerus with respect to the trunk. Whilst this is not an anatomical joint, this simplification is less likely to be affected by the movement of soft tissue than the alternative of modelling the scapula. It is accepted that the elevation of the scapula may play an important role in tennis groundstrokes, as the upper arm can not abduct at the shoulder by more than 90° without scapula elevation (Totora and Grabowski, 2000) and the upward movement of the arm may be an important factor in topspin generation (Knudson, 1991). This is an obvious limitation in terms of modelling accuracy, however it was felt that the result of this motion could be analysed through the global movement of the upper limb. The trunk segment was modelled as a single unit defined by the acromion processes of the scapula and the posterior superior iliac spine. It was tracked by four markers placed directly onto the skin. The humerus was modelled at the distal end through the medial and lateral epicondyles, and by two methods at the proximal end. The first of these was a prediction of the centre of rotation with respect to the acromion process of the scapula, whereby the distance from the acromion process to the palpated proximal head of the humerus was measured and an inferior offset applied from that (Schmidt *et al.*, 1999). This was termed the 'predictive' method. The second was based on the ISB's (Wu *et al.*, 2005) preferred method of calculating the pivot of several instantaneous helical axes, termed the 'functional' method. The creation of the functional joint is based on movement of the upper limb cluster with respect to the trunk and was calculated using the method of Schwartz and Rozulmalski (2005). The movement itself was a small circumduction of the humerus, with limited elevation so that the position of the scapula remained fixed (3.1.2.2). Therefore, the centre of rotation of the humeral head in the glenoid fossa was calculated rather than the entire shoulder complex. The method of calculation uses the sample mode of all possible outcomes (Schwartz and Rozumalski, 2005) where the axis of the upper arm moves relative to the trunk.

The two methods of locating the gleno-humeral centre of rotation were compared using a range of movements. A participant (Age 26, Height 1.7 m, Mass 65 Kg) performed abduction, elevation in the sagittal plane, a horizontal arm swing similar to a discus throw, an out of plane vertical arm swing and a tennis forehand stroke. The abduction and elevation movements corresponded to an approximate ROM of 90°, therefore providing an expected target for calculation of joint kinematics. Movement was captured at 240Hz using an 8 camera motion capture system (Qualisys AB Medical, Sweden). Trunk and upper arm segments were constructed as previously described (3.1.2), and marker data was smoothed using a 20Hz low-pass 4th order Butterworth filter, deemed subjectively to remove signal noise whilst maintaining the characteristics of the signal.

Shoulder kinematics for the five movements were calculated using the Euler sequences 'XYZ', 'YZX', 'ZYX', 'YZY' and 'ZYZ' in relation to the anatomical axes (Figure 3.5). The Euler sequence 'ZYZ' corresponds to the recommended sequence describing humeral movement in relation to the thorax given by the ISB (Wu *et al*., 2005), and the 'XYZ' sequence is a common description of lower limb kinematics. The other sequences were chosen for further comparison, and in order to provide further sequences where the first rotation corresponds with that of the movement of interest as recommended by Cappozzo *et al*. (2005).

Each aim was assessed by the same criteria; did the ROM match up with expected motion in the principle axis of movement, and what was the amount of cross-planar talk observed in the other axes. The functional and predicted gleno-humeral joint centres were assessed by comparing the kinematics in all three planes of motion on the above criteria. The chosen method of defining the proximal head of the humerus was then used to judge the suitability of each Cardan/Euler angle sequence for each type of movement. These judgments were easier to make based on the simpler movements of abduction and elevation where the movement was almost entirely in one plane. However, it was also necessary to make judgments regarding more complex movements based on the cross-planar motion associated with the tennis groundstrokes.

3.2.3 RESULTS AND DISCUSSION

The first aim of the investigation was to compare the shoulder kinematics derived from an upper arm segment defined at the proximal end by predictive and functional methods. The predicted position of the gleno-humeral centre of rotation from the acromion process of the scapula and the calculated functional joint provided comparable kinematics (Figure 3.6). Clear similarities in ROM are observed between the traces, but with an offset between the two methods. Similar patterns were observed for the other movements analysed. The reason for the offsets is likely to be due to the relative position of the humeral head in the coronal plane. There was an observable difference in the model in this plane, with the position calculated by the functional method more medially located than the predictive method. Irrespective, of the method of locating the proximal end of the humerus, the movement patterns were not the same for any two planes of motion, indicating the absence of cross-planar talk. As neither method resulted in kinematics that were outside of the ROM expected and neither produced observable cross-planar talk, this analysis has not been able to determine a preference for a particular method. Therefore, as the preferred method of the ISB (Wu *et al.*, 2005), the functional provides a sensible choice for the description of the proximal end of the humerus. Given the offsets between these methods, it would seem sensible to base conclusions on the ROM of the shoulder rather than absolute values.

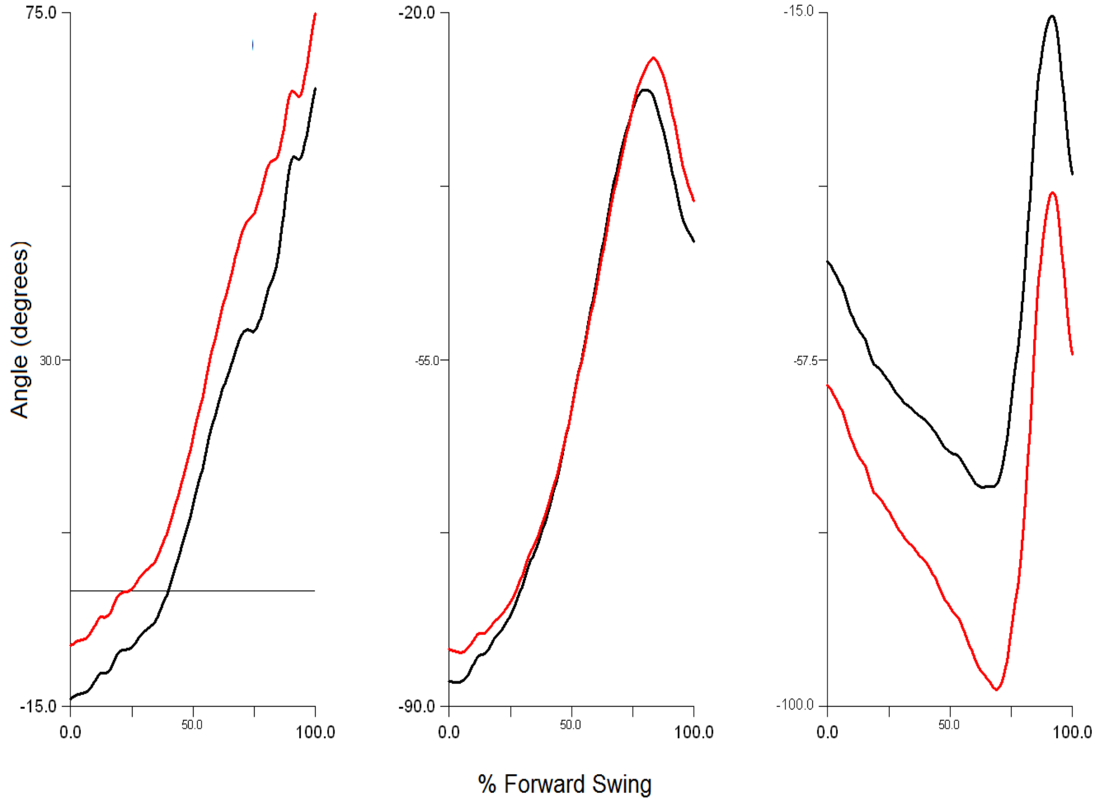


Figure 3.6 – Calculated shoulder kinematics using the Euler ZYZ sequence of rotations in the three cardinal planes namely; movement around the trunk (left), abduction (middle) and axial rotation (right). The black traces represent the kinematics calculated by the humerus segment calculated through the functional joint method, whilst the red traces represent a predicted joint centre.

The second aim of the investigation was to assess the suitability of a number of Cardan/Euler angles sequences for movements at the gleno-humeral joint, particularly during a tennis forehand. The judgments for each movement are summarised in Table 3.3. The rationale for the decision is illustrated in relation to the forward swing for the forehand tennis groundstroke.

Table 3.3 – The optimal Cardan / Euler sequences for each movement.

Movement	Abduction	Elevation	Horizontal swing	Vertical swing	Tennis Forehand
Optimal Sequence	XYZ	XYZ, YZX	ZYZ	ZYZ	ZYZ

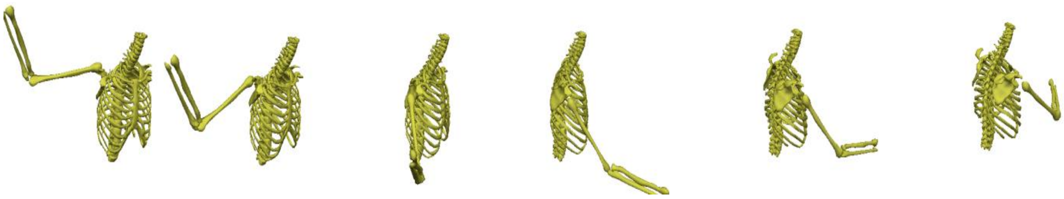
The results were in agreement with Šenk and Chèze (2006) that the ISB recommended sequence of 'YXY' ('ZYZ' for the axes used here) (Wu *et al*., 2005) does not provide meaningful angles for all movements of the upper limb with respect to the trunk. However, the recommended sequence does provide angles in the coronal and transverse planes during the forward swing of the tennis forehand stroke.

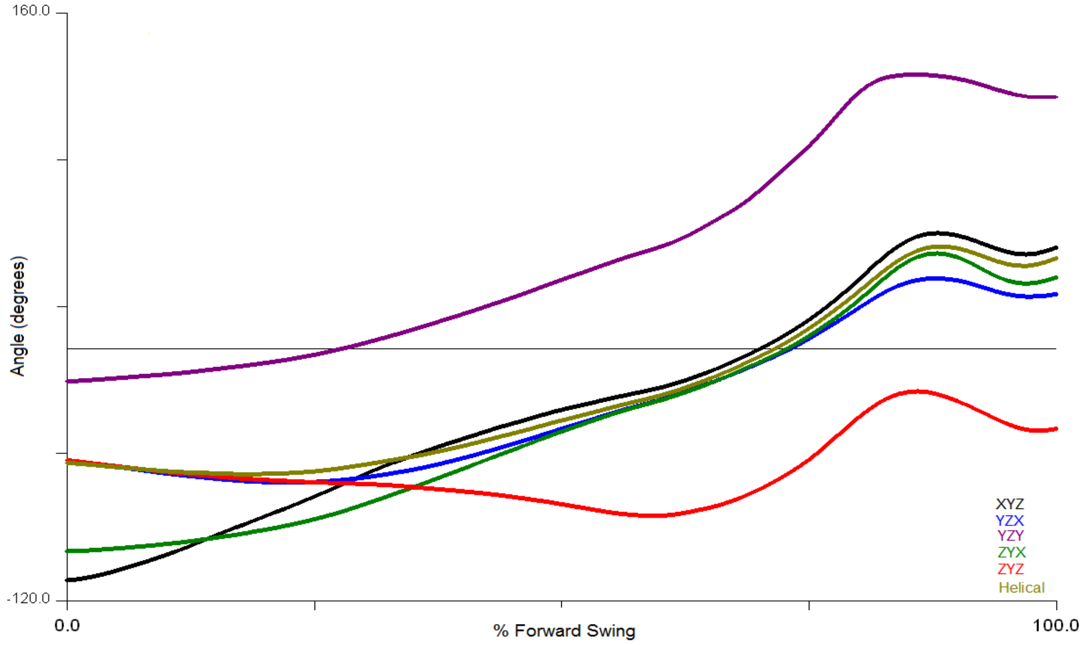
The movement at the shoulder during the forward swing of the racket in the stroke analysed (Figure 3.7) is a combination of adduction and internal rotation. Much of the movement of the racket through the stroke appears to be as a result of the rotation of the trunk, not the independent movement of the humerus in the sagittal plane. This forward rotation of the trunk has been identified previously as important for the generation of forward racket velocity (Elliott *et* al., 1997). Therefore, the limited importance of sagittal plane movement of the upper arm with respect to the trunk provides some justification for the ISB recommended Euler sequence, which excludes this movement. Furthermore, the coronal and transverse angles (Figure 3.7) demonstrate contrasting patterns of movement for the ZYZ sequence, indicating that there is no cross-planar talk.

Much of the early movement, indicated by the first three images (Figure 3.7a) at the shoulder is adduction, not axial rotation, yet only the 'ZYZ' description has a limited ROM of axial rotation in this phase. In the later phase of the movement, indicated by the later images (Figure 3.7a), there is axial rotation of the humerus, that combines with the rotation of the trunk, to bring the racket forward, which is shown for most of the sequences. The earlier discrepancy may be due to the anatomical rotations that Z represents for the different sequences. Wu *et al*. (2005) explain that the first rotation in Z in the 'ZYZ' sequence is the rotation of the humerus about the long axis of the trunk, or more colloquially, movement of the upper limb around the trunk. The second rotation, Y represents abduction, and the third rotation Z represents axial rotation of the humerus. It is possible that the other Cardan/Euler sequences in Figure 3.7a are describing the movement about the trunk and the axial rotation of the humerus, explaining the exaggerated rotation in the early phases of the forward swing.

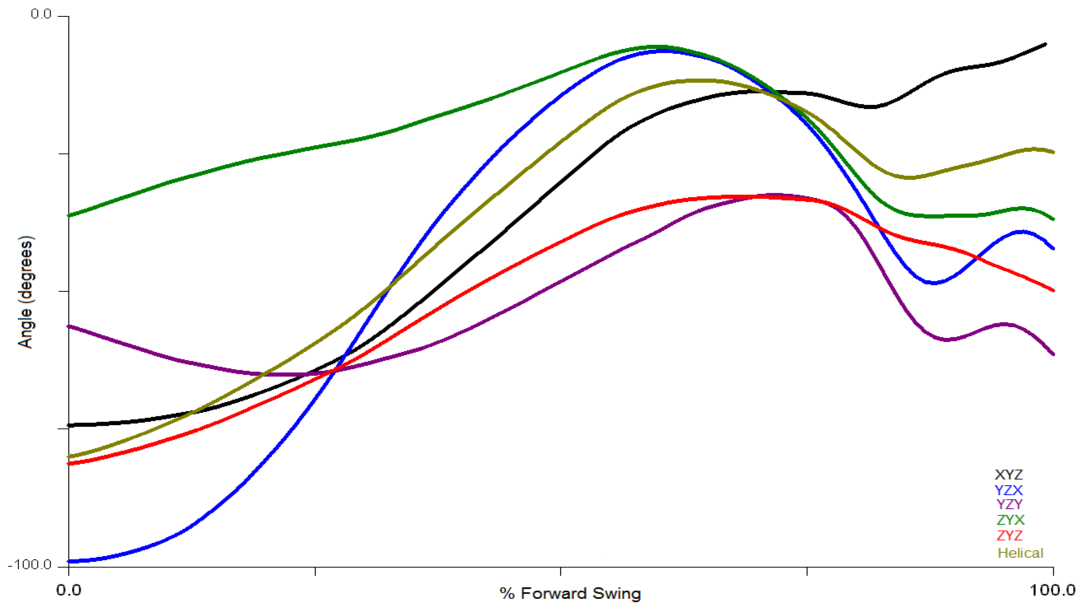
The adduction of the humerus with respect to the trunk (Figure 3.7b) is represented by each Cardan/Euler sequence that was evaluated. However, there was discrepancy in the ROM calculated. The movement indicates adduction of 40-60° in the early phase of the movement (Figure 3.7b), followed by a limited ROM thereafter. However, the earlier adduction seems to be overestimated by all, except ‘ZYZ’ and ‘ZYX’ sequences. Interestingly, the ‘XYZ’ sequence was judged to provide an accurate description of abduction in an isolated movement, but was less accurate in describing this movement in a cross-planar activity.

This assessment of Cardan/Euler angles supports the contention of Šenk and Chèze (2006) that not all sequences will provide meaningful anatomical results for all movements. However, the ISB recommendation for defining the humerus and describing shoulder kinematics was shown to provide a good description of the forward swing of the tennis forehand groundstroke.





a)



b)

Figure 3.7 – Mean curves of (a) the axial rotation of the humerus segment and (b) the adduction of the upper arm with respect to the trunk during the forward swing of the forehand stroke. The images represent the movement presented in the graph at equal intervals of time, but do not necessarily correspond exactly to their position on the graph in time.

3.3 FILTERING OF KINEMATIC SIGNALS

3.3.1 INTRODUCTION

The methods by which white noise is removed has been questioned on the grounds of the method of filtering (Knudson, 1990) and the choice of cut-off frequency based on the method used (Giakas and Baltzopoulos, 1997a) and the derivative of interest (Giakas and Baltzopoulos, 1997b). Previous research investigating tennis kinematics have routinely removed higher frequencies with cut-off frequencies in the range of 4-12 Hz, however this may not be adequate for the impact phase of activities where the frequency content of this phase differs dramatically from the rest (Nunome *et al*., 2006). Knudson (1990) demonstrated that smoothing routines through the impact phase of a tennis forehand distorted both the timing and magnitude of impact phase kinematics. The present study is concerned with the kinematics of the forward swing in tennis groundstrokes to impact, and therefore the distortion of kinematics in this phase would place limitations on the results obtained. Therefore, it is important to quantify any such distortion and minimise it.

The method by which cut-off frequency is chosen is seldom reported. However, Giakas and Baltzopoulos (1997a) demonstrated that many automatic signal filtering techniques produced inconsistent results, and this may explain an apparent lack of trust in any particular method. Furthermore, they demonstrated that the choice of cut-off frequency is dependent on the derivative of interest. The present study is concerned with velocities of joints and segments in the impact phase of the tennis groundstrokes, and thus the choice of cut-off frequency will reflect this.

The aim was to determine the optimal cut-off frequency for a typical tennis groundstroke using a low-pass Butterworth filter with respect to the phase of the stroke with the highest frequency content. As displacement and velocity data are routinely used in analyses of tennis groundstrokes (Lees, 2003), each of these was given consideration.

3.3.2 METHOD

One participant (Age 18; Mass 71.8 kg: Height 1.82 m) was instructed to hit ten forehand groundstrokes. Data capture methods were replicated a previous analysis (3.2.1). The displacement and velocity vectors of the racket were derived from the square root of the sum of squares for each orthogonal direction. These signals were chosen as representative signals for analysis due to the expected high frequency content at racket-ball collision. A low-pass 4^{th} Order Butterworth digital filter was applied to the unfiltered signal at 1 Hz intervals, beginning at 1 Hz and continuing to 30 Hz. The thirty filtered signals were then compared to the unfiltered data in terms of the change in the magnitude of the peaks at impact and the phase shift of the peaks. It is acknowledged that the unfiltered signal with which the comparisons are made is, by definition, not a perfect signal due to the presence of white noise. Therefore, visual inspection of the data by means of graphical output was also used in support of the quantitative data.

3.3.3 RESULTS AND DISCUSSION

The cut-off frequencies altered the magnitude of the displacement peak by less than 5% of the original signal typically at cut-offs of 6-7 Hz (Mean 7.13, Median 6, Mode 6) and above. The positioning of the peak displacement data remained unchanged in time. However, the first derivative data was distorted at these frequencies, indicating that true signal may be lost. The peak velocity was reduced by greater than 5% until 23 Hz for all, except two, trials (Mean 22.25 Hz, Median 24.5 Hz, Mode 27 Hz).

The cut-off frequency was set at 25 Hz. This value does not produce a phase shift of greater than two frames in any instance for this data set. Visual inspection of the data (Figure 3.8) confirmed this cut-off frequency as a level that retains the characteristics of the original signal.

This method has determined a cut-off frequency that will retain the characteristics of the original signal with minimal distortion in terms of both magnitude and timing in the impact phase of the tennis forehand. It is noted that the unfiltered data used for comparison is contaminated with noise and can not be seen as the ‘gold standard’. However, given the comparison with the filtered signals in the other phases of the movement, it provides a reasonable comparison. Furthermore, the cut-off frequency is likely to affect other signals with lower frequency content to a lesser extent as the representative signal chosen is one believed to contain the highest frequency of signal.

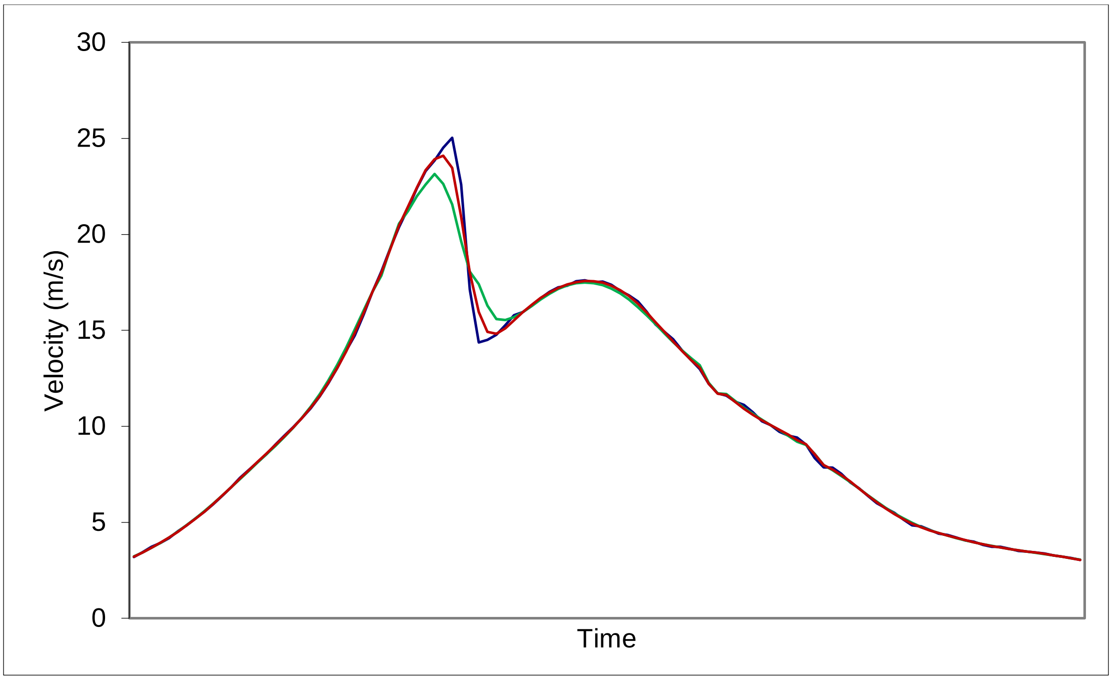


Figure 3.8 – Representative velocity vector of one trial. The largest peak on the chart indicates the maximum velocity of the racket at the approximate point of racket-ball collision. The cut-off frequency choice of 25 Hz (dark red line) is compared to the unfiltered signal (blue line) and exemplar data of 15 Hz (green line).

3.4 QUANTIFICATION OF THE SPIN RATE OF THE TENNIS BALL

There are a limited number of examples whereby full details of methodology for tracking the spin of a tennis ball have been given (Chapter 2.2). Of those that have provided details (e.g. Kelley *et al*., 2008), the spin rate has been tracked over at least one full revolution of the ball. These studies have captured footage in a match or practice environment, and were recorded a reasonable distance from the ball itself. The laboratory environment for the present study will not enable such a set up to be replicated. This is due to the positioning of the camera in order to capture ball flight at an angle perpendicular to the lens of the camera. Furthermore, the focal length of the camera is not sufficient to maintain a clear image at a distance greater than 10 m. Therefore, the field of view was reduced in comparison to the studies of Goodwill *et al*. (2007) and Kelley *et al*. (2008), meaning a shorter period of the ball flight could be captured. However, the accuracy of the flight that was recorded is likely to be improved due to the improved pixel resolution from this distance.

Following preliminary investigations it became clear that, for most players, the period of time that the ball was in clear focus was not sufficient for the ball to rotate through one full revolution. Therefore, instead of adopting the approach of calculating the spin rate based on the time taken for one or two revolutions, spin was calculated based on the number of revolutions or partial revolutions over a specific time period. The time period suitable for all players, irrespective of the velocity of shot was found to be 20 frames, or 0.02 s.

The amount of ball spin has been calculated based on the rotation of the manufacturers' logo in previous studies (e.g. Goodwill *et al*., 2007), but this method does lead to a number of discarded trials if the logo is not visible throughout the measurement period. Therefore, the present study attempted to increase the success rate of measurement in terms of the number of trials discarded. The options investigated were painting the ball with a felt marker to add colour to the seam, colour half the ball, paint the ball in quarters and paint different shapes on a number of surfaces. It was decided that the felt paint would do little to alter the natural characteristics of the ball, but provide some distinction between light and dark on the ball in the black and white image filmed.

The primary task in the digitising process was to identify an axis, using the contrast of painted and unpainted felt, which was visible throughout the twenty frames of data. A line was then drawn along the chosen axis using a two-point collection model for each frame of data. The success of each method of painting the ball was judged, subjectively, by how frequently an axis could be identified on the ball throughout the entire twenty frames of data.

The quartered ball (Figure 3.9) was most successful in providing an axis that could be consistently tracked throughout the twenty frames captured for analysis. The number of trials discarded from the main study (42 out of 400) supports the use of this method of marking the ball in improving tracking of the spin of the ball.

Figure 3.9 – Pattern of paint used on the ball that allowed the spin rate to be calculated most frequently

3.5 SUMMARY OF CONCLUSIONS

- The International Society of Biomechanics recommendation for the determination of angular motion at the shoulder provided an anatomically meaningful representation of the kinematics during the forward swing of the forehand tennis groundstroke.

- A custom-made planar rigid cluster design was found to measure an isolated axial rotation of the forearm segment to the highest degree of accuracy.

- Distal placement of the forearm and upper arm segment rigid clusters reproduced accurate axial rotation of the forearm, but with minimal error in other planes due to soft tissue artefact.

- Despite the limitations of digitally smoothing kinematic data through the impact phase a Butterworth low-pass filter was demonstrated to remove white noise whilst maintaining the characteristics of the velocity peak at racket-ball impact in a tennis forehand.

- Methodology was developed for the tracking of the spin of a tennis ball using a high-speed video camera.

4.METHODS

4.1 PARTICIPANTS

Following ethical approval from the University of Central Lancashire ethics committee, twenty tennis players (Age 25.39 ± 13.20 years; Height: 1.75 ± 0.12 m; Mass 70.21 ± 12.30 kg) gave their informed consent (Appendix B) to take part in the study. Of these, fourteen were male and six were female. The players had varying experience in the game, but had all played tennis for at least five years. Playing level also varied ranging from local club players to county-level, but all played regularly for their club and/or, their University. Nineteen participants were right-handed, and thirteen played the back hand using a two-handed approach. Prior to testing each participant completed a health screening questionnaire (Appendix B) to confirm that they were injury-free and did not have any pre-existing medical condition that would prevent them from participating.

4.2 SET UP AND APPARATUS

All participants used either a Prince Thunder Series (grip size 3) or Prince Vendetta Series (grip size 4) carbon-fibre composite racket (Figure 4.1) to control for variations in spin rates due to the properties of the racket. Prior to testing, each racket was strung with natural gut at a mid-range tension, and restrung approximately halfway through the data collection. Although small variations exist between the rackets, it was hoped that these would be negligible compared to the variations in stroke technique. Each racket was defined proximally by two markers placed at the throat, and distally by the marker at the tip (Figure 4.1). The additional markers were used to track the movement of the racket in three-dimensional space. The markers were screwed to the frame by drilling holes as close to the centre of the racket as possible so that the axes of the racket could be accurately defined in relation to the strings.

Figure 4.1 – Prince Thunder Series grip size 3 (left) and Vendetta Series grip size 4 (right) rackets

Participants stood towards the back of the 3D analysis collection zone, to the right of the diagram (Figure 4.2a), which allowed the participants to be in the field-of-view of the motion capture cameras (Figure 4.2b). They then received a delivery from a pneumatic ball machine (MDL 300 Series, Lob-ster, USA) (Figure 4.3). Due to the close proximity of the ball machine to the analysis area, it was raised on a stable trolley in order for the ball to bounce prior to the analysis area and arrive at a height that was comfortable for the participants to return to the target area (Figure 4.2a). The ball machine was adjusted slightly in order for a realistic delivery (approximately waist height) to be achieved for all participants, with the angle of the ball machine to the horizontal at approximately 45°.

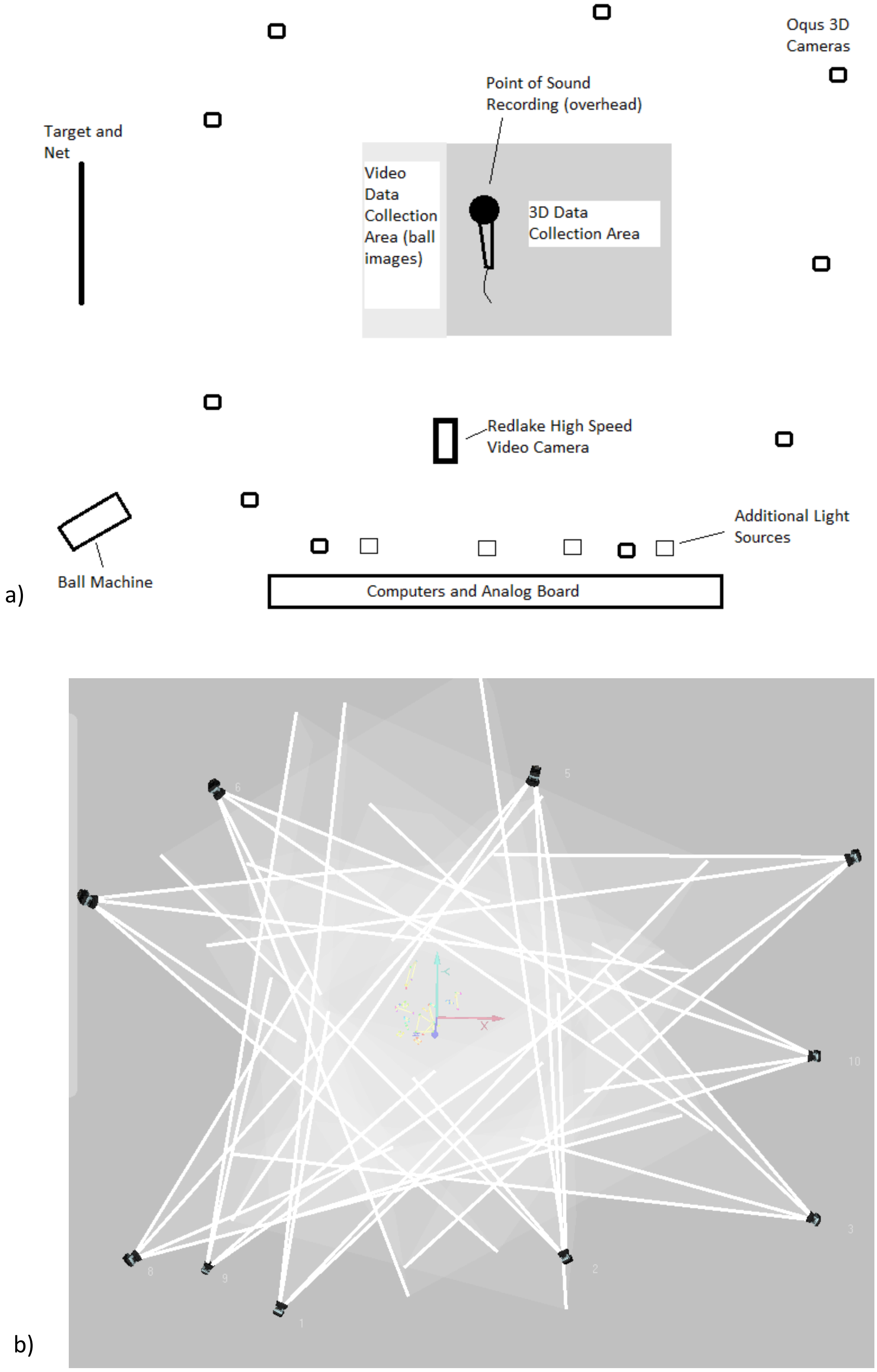


Figure 4.2 – Laboratory set up as viewed from above. a) Plan view, not to scale. b) 3D camera positions of 10 camera Oqus system (Qualisys AB Medical, Sweden) and corresponding view of each.

The accuracy of the ball machine was ascertained by recording the spin rate, velocity and height of the ball once it had reached the edge of the target area. High-speed video (MotionScope M1, Redlake, USA) footage with a frame rate of 1000 Hz was used to establish these parameters over 20 trials using the same ball, and a further 20 trials using different balls. The mean spin rate for all 40 trials was 1510.21 rev.min^{-1}, with a velocity of 10.69 m.s^{-1}, and bounce height of 0.37 m. Based on the coefficient of variation for each of these measures, the variability when the same ball was used was 110.10 rev.min^{-1}, 0.38 m.s^{-1} and 0.04 m for spin rate, velocity and bounce height respectively. When different balls were used the variability of spin increased to 153.35 rev.min^{-1}, but the variation reduced slightly for velocity and height at 0.24 m.s^{-1} and 0.04 m. For all trials the variation was 138.64 rev.min^{-1}, 0.39 m.s^{-1} and 0.04 m. The results indicate that the ball machine provides a consistent delivery to the participant, with no evidence to support increased variation due to using a selection of balls throughout testing. Nevertheless, the condition of the balls was monitored prior to each testing session. New Slazenger Wimbledon Ultra Vis tennis balls were used throughout testing and were replaced once the rebound ratio dropped from an initial value of 0.62 to less than 0.56 (90 % of initial value).

Figure 4.3 – MDL 300 Series pneumatic ball machine (Lob-ster, USA). It was raised, and the angulations altered due to the proximity to the analysis area.

A target was constructed to control for the type of stroke played (Figure 4.4). The net was hung at a regulation height of 0.91 m at the centre, and the frame restricted the maximum height of the stroke to be 2.44 m leaving a vertical window of 1.53 m, with a horizontal width of 2.49 m The proximity of the analysis area to the positioning of the target meant that the stroke played was representative of a player stepping into court to play a stroke, rather than from the baseline. The positioning of the target was such that the strokes played were representative of a ‘down-the-line’ shot. This stroke is often played as a means of winning a point, rather than gaining tactical advantage, due to the position of the players on the court (Williams and Petersen, 2000). It is also a stroke where playing with topspin could be beneficial, as the parabolic flight path of a topspin stroke would help to clear what is the highest part of the net (ITF, nd).

Figure 4.4 – Target in which participants were required to play their stroke into.

A microphone was suspended above the 3D analysis area in order to record the collision between ball and racket. This data was transferred through a mixing desk and into an analogue channel feeding into the analogue-to-digital converter. This produced a clearly defined spike at the moment of ball-racket impact within the movement analysis software (Figure 4.5) (Visual 3D, C-Motion, USA), which was used to generate an event. The distance between the microphone and racket at the point of ball collision was estimated. This information was then used to adjust the event in the motion analysis software, owing to the delay due to the speed of sound, which is approximately 343 $m.s^{-1}$ at a temperature of 20°C (Hecht and Bueche, 1997). This delay varied within, and between, participants as each collision did not occur at precisely the same point in space. However, this magnitude was generally within 2 metres, therefore only corresponding to approximately two frames of motion data at a sample frequency of 300 Hz.

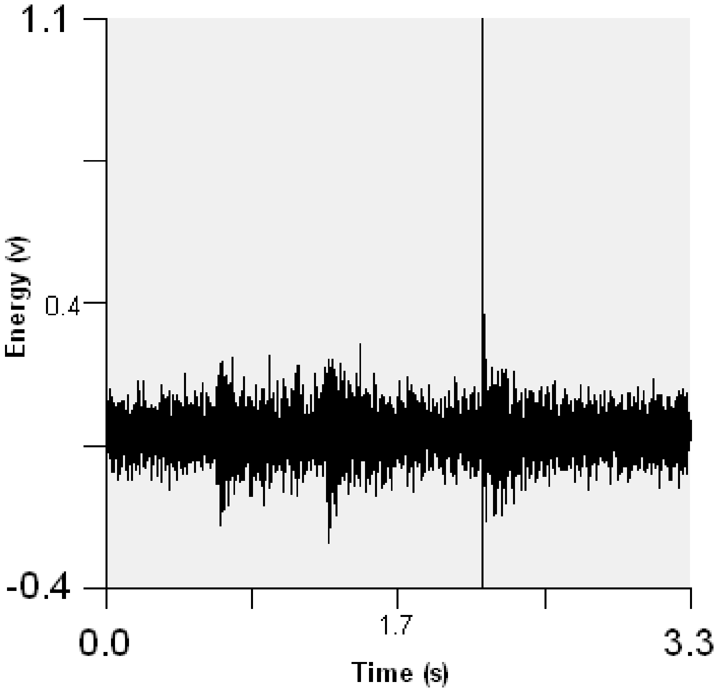


Figure 4.5 – Exemplar of the analogue signal used to determine ball-racket impact. The first peak above the baseline of white noise was considered the point of impact. This was the adjusted to account for the speed of sound

The motion of the ball following racket-ball collision was tracked using a high-speed video camera (MotionScope M1, Redlake, USA) operating at 1000 Hz, with an exposure time set at 200 µs. Additional light sources (Figure 4.2a) allowed the lens aperture to be set between f/0.95 and f/1.4. This is a similar set up to that used by Goodwill *et al*. (2007) indoors and Kelley *et al*. (2008) outdoors. These studies have demonstrated that these settings can minimise the motion blur associated with high-frequency movement, whilst maintaining a reasonable depth-of-field. The screen resolution was fixed at 640 x 512 pixels. The camera was positioned perpendicular to the target, with a field of view approximately corresponding to the diagram (Figure 4.2a). This position was chosen to capture the maximum amount of ball flight possible following racket collision, whilst the perpendicular position represented an attempt to minimise parallax error.

The motion of each participant was captured using a ten camera three-dimensional optoelectronic movement analysis system (Qualisys AB Medical, Sweden), with a capture frequency of 300Hz. The accuracy of the system was evaluated prior to testing, by moving a wand of markers of a known calibrated length through a number of configurations. These included moving the wand horizontally and vertically at different aspects, and cross-planar movements such as stirring and spinning motions (Figure 4.6).

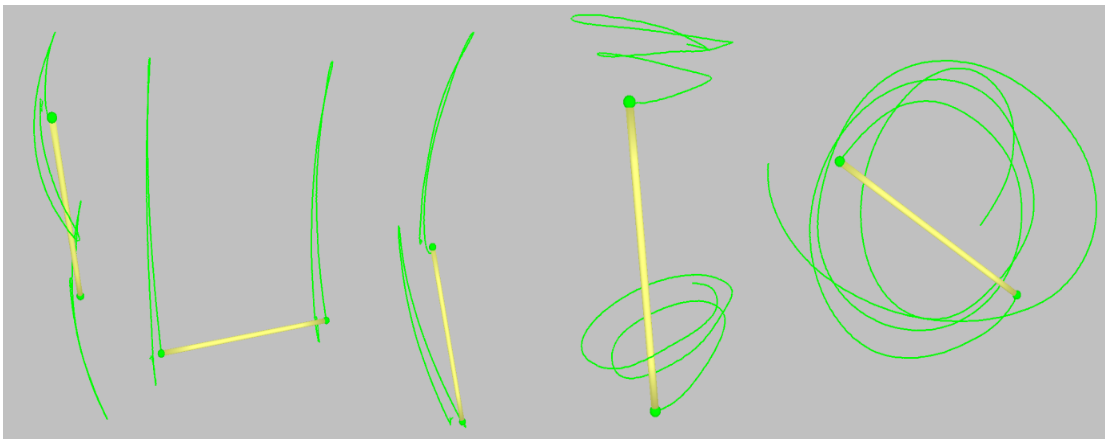


Figure 4.6 – The configurations the wand was moved through to ascertain the error of the motion capture system.

The maximum error in the calculation of wand length over four seconds of data, during any trial, irrespective of movement, was 2.24 mm. However, each measure of central tendency indicated that the average error was 0.20 mm. The more complex stirring and spinning motions did invoke larger maximum errors than the planar movements, but the mean tendencies remained unchanged. The results presented here indicate that system error is unlikely to significantly affect any of the results obtained in this study.

Passive reflective markers were placed on participants to reconstruct the movement of the underlying bone in three dimensional space (Figure 4.7). The full body model is based upon the Calibrated Anatomical Systems Technique (CAST) (Cappozzo *et al.*, 1995), whereby a rigid cluster of at least three non-collinear markers is used to track the movement of a body segment. These are referenced to the anatomical end-points of a segment by the means of a static calibration. Following the static calibration, the anatomical landmarks were removed.


Figure 4.7 – Position of anatomical and technical markers (size 19mm diameter).

The anatomical markers (size 19mm diameter) were placed such that a 13-segment model was constructed. This comprised the pelvis, trunk, bilateral thigh, shank, foot, upper arm and forearm segments and the racket. Each segment is defined by a pair of markers at proximal and distal ends, with the foot defined proximally by the medial and lateral malleolli of the tibia and fibula respectively and by the first and fifth metatarsal heads at the distal end. The shank is defined proximally by the medial and lateral epicondyles of the femur and distally by the medial and lateral malleolli of the tibia and fibula respectively. The thigh is defined proximally at the hip joint centre, from a projection from the greater trochanter of the femur and distally at the medial and lateral epicondyles of the femur. The hip joint centre is generally calculated using the ASIS anatomical landmarks (Bell *et al*., 1990; Davis *et al*., 1991), but these landmarks were not reliably tracked throughout the movement for all participants. Therefore, a participant-specific medial projection from the greater trochanter was used. For each participant, the position of the hip joint centre was estimated by projecting medially from the greater trochanter marker, based on a measurement made with a rule. The measurement was taken from the medial aspect of the marker on the greater trochanter to the estimated centre of the segment to provide a radius for the proximal end point of the thigh. The measurement was made only in the coronal plane, with no offset along the longitudinal axis of the segment. The mean magnitude of this projection from the greater trochanter was 0.081 ± 0.005 m. Projections from the greater trochanter have produced comparable hip joint centre locations to functional and regression methods (Weinhandl and O'Connor, 2010). However, the difference in procedure between the present study and previous projection methods mean that there is likely to be error in the location of the hip joint centre. This can significantly affect kinematics in the coronal and transverse planes (Della Croce *et al.,* 2005). However, this study is only concerned with sagittal plane kinematics of the lower limbs, which is less likely to be influenced by this approach.

The pelvis is defined proximally by the right and left iliac crests and distally at the greater trochanter. The trunk is also modelled as a single segment defined proximally at the posterior superior iliac spine (PSIS) and distally at the right and left acromion processes of the scapula. This segment may be partitioned into several sections (Zatsiorsky, 1998) due to its morphology. However, the amount of skin movement in relation to the underlying bones, particularly the scapula and clavicle (Rau *et al*., 2000) makes this type of modelling difficult. It was felt that the rotational nature of the tennis groundstrokes were likely to exacerbate these kind of errors, and therefore any benefit derived from modelling the trunk in multiple segments would be outweighed by the errors from soft tissue artefact. The hand was not modelled, owing to difficulties tracking this segment, meaning that wrist kinematics could not be calculated. Previous analyses have identified types of forehand (Elliott *et al.*, 1997) and backhand (Reid and Elliott, 2002) grips, but have not established whether a particular grip is beneficial for producing topspin. The grip itself is likely to remain relatively stable throughout the stroke, whereas the present investigation is concerned with the kinematic changes during the stroke and at impact that are related to the production of topspin. Therefore, while it would be interesting to be able to measure variations in grip between participants it is not the main focus of the investigation and is not a major limitation. Movement at the wrist was calculated through the relative positions of the forearm and racket. This does not provide any information that can be related to anatomical movement, but does provide information regarding the extent of the movement.

There were some exceptions to the definition of segment end-points. The forearm is defined proximally at the mid-point of the medial and lateral epicondyles of the humerus and distally at the radial and ulnar styloids. The proximal end is defined only as a single point as the aforementioned reference points do not correspond with the anatomical axes of rotation. The humerus is constructed from a functional joint centre representing the centre of rotation at the gleno-humeral joint centre (Schwartz and Rozumalski, 2005) and distally at the medial and lateral epicondyles of the humerus. The functional method provides a more reliable method of attaining a joint centre that is not easily described using an anatomical frame, such as the hip or shoulder. Participants were required to move their arms in such a way that maximised the ROM, but did not alter the position of the scapula in any way. Practically, this was only a limited movement consisting of small circular movements with the arms adjacent to the trunk. This movement resulted in an observationally correct positioning of the head of the humerus in the glenoid cavity of the scapula, and was considered preferable to a projection from the acromion process of the scapula.

A technical cluster of four non-collinear markers moulded within a lightweight carbon-fibre plate was mounted onto each limb segment. This facilitated the removal of the anatomical markers from these segments once a static calibration file had been captured. The foot, pelvis and trunk segments were also defined relative to a technical coordinate system of markers, but these were not placed on a rigid shell. This was due to the morphology of these segments.

4.3 PROCEDURE

Participants were required to hit at least eighty groundstrokes, with twenty successful strokes that were hit into a target recorded for analysis. These numbers were broken down over four conditions; forehand played with topspin, forehand hit flat, backhand played with topspin and backhand hit flat. Therefore, a minimum of twenty strokes were played for each condition, with five of those recorded. The groundstrokes were played in blocks so that each participant played the same stroke until all trials for that condition were recorded. The order of conditions was not randomised between participants, as participants were asked to nominate the stroke that they would like to begin with, or felt most comfortable playing. This allowed them to get used to the laboratory environment with a choice of shot they felt comfortable with.

Prior to the commencement of testing participants were allowed to practice, and this served as a warm up for them whilst also allowing the investigators to check the set up of the equipment in relation to the participant. During this time some minor adjustments were made to the positioning of the ball machine to ensure that the delivery arrived within the 3D analysis area (Figure 4.2) at a suitable height for the participant to play the stroke. Minor adjustments were also made to the positioning of the high-speed camera if necessary.

Once an experimental condition was selected and the participant was familiar with the procedure, four Slazenger Wimbledon Ultra Vis tennis balls were loaded into the ball machine (MDL 300 Series, Lob-ster, USA). The ball machine was then activated by means of a remote foot switch to release the four balls from the hopper. Only one of the four strokes was recorded for analysis by the three-dimensional motion capture system (Oqus, Qualisys AB Medical, Sweden) and the high-speed video camera (Redlake MotionScope M1, USA). The capacity of the internal memory of the high-speed video camera prevented recording of more than one trial, however it was decided that the other three balls in the hopper should be delivered too. It was felt this provided a measure of ecological validity to the investigation, as tennis players rarely play only a single stroke in a rally. The participant was unaware of which of the four deliveries was recorded. This procedure was repeated until five trials from each condition were recorded. Five trials have been shown to be a reasonable number to provide stability to kinematic data (Knudson and Blackwell, 2005). It was felt that further trials may prove fatiguing for participants, and in this respect the investigation attempted to gain a balance between the variability of the data and the ecological validity. Approximately one minute rest between each recorded trial was afforded the participants whilst the video data was saved onto a computer and the hopper of the ball machine was reloaded, which further served to reduce the effects of fatigue.

4.4 DATA ANALYSIS

The three-dimensional motion capture data was recorded for a period of 3 seconds per trial. The coordinate data was identified and then exported, using Qualisys Track Manager software (Qualisys AB Medical, Sweden), into a specialist motion analysis package (Visual 3D, C-Motion, USA). The coordinate data was filtered using a 4th order 25 Hz Low-pass Butterworth digital filter, previously determined as suitable for the impact phase of the movement (Chapter 3, section 3). A full body model was created, as described previously, with segment coordinate axes constructed based on the right-hand rule (Figure 4.8). Joint angles were calculated using a Cardan 'XYZ' sequence, corresponding to the anatomical axes of motion in the sagittal, coronal and transverse planes. The exception to this was at the shoulder joint, whereby the Euler 'ZYZ' sequence was implemented as recommended by the International Society of Biomechanics (ISB) (Wu *et al*., 2005). This sequence describes movement around the trunk, followed by movement away from the trunk and finally, rotation about the long axis of the humerus. Joint angles and velocities described motion at the knee, hip, pelvis, shoulder, elbow, and between the forearm and racket. The rotation of a segment was described in relation to the proximal segment in all planes. Velocities of body segments and the racket were calculated with respect to the global coordinate system, with Z describing vertical movement. Segment velocities were calculated at the humerus, forearm and racket.

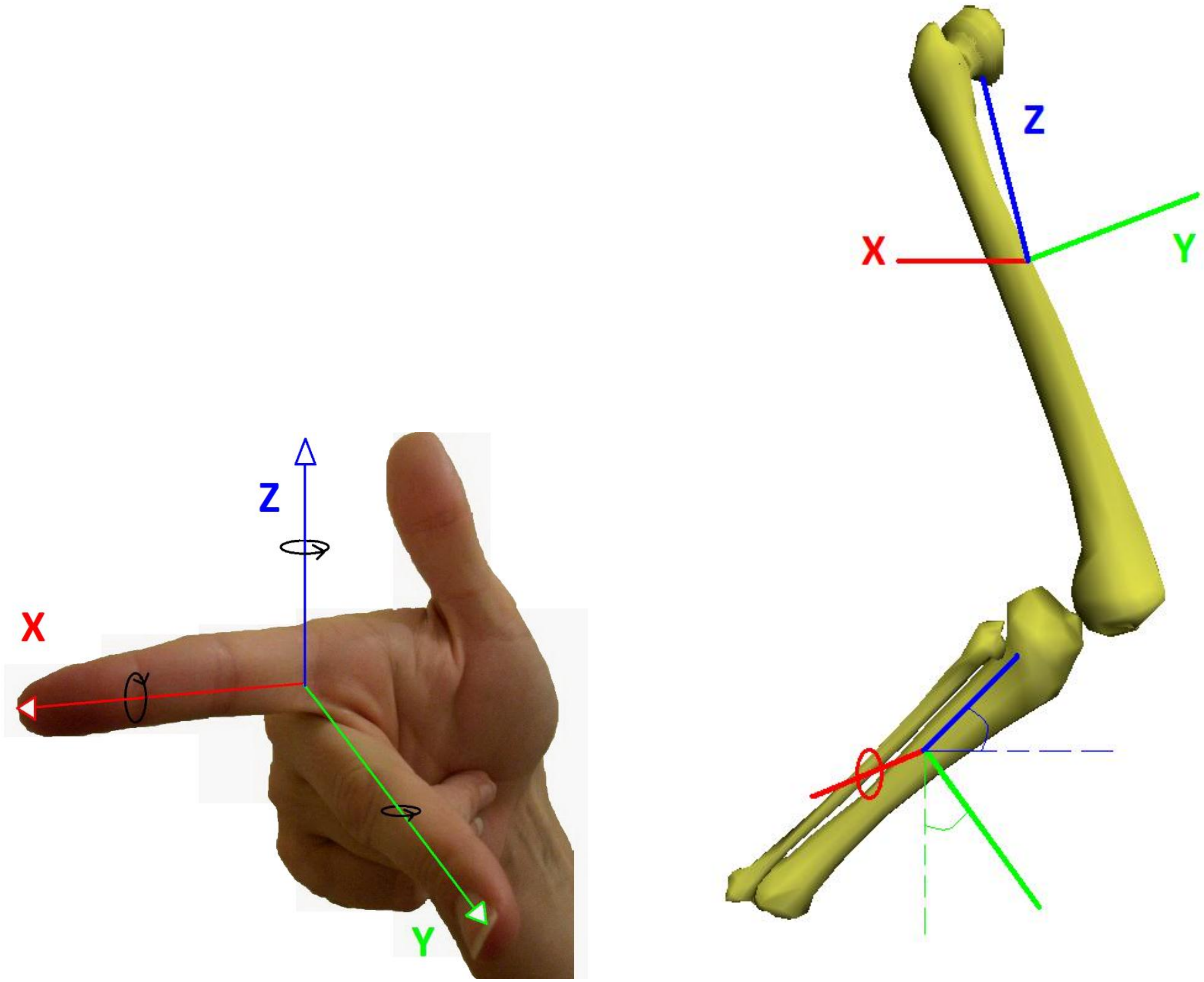


Figure 4.8 – Right-Hand definition of axes used to calculate kinematics. The knee joint is presented as an example of the 'XYZ' order of rotations used for all joint calculations, with the exception of the shoulder. This corresponds to ordered anatomical rotations in the sagittal plane , coronal plane, then transverse plane.

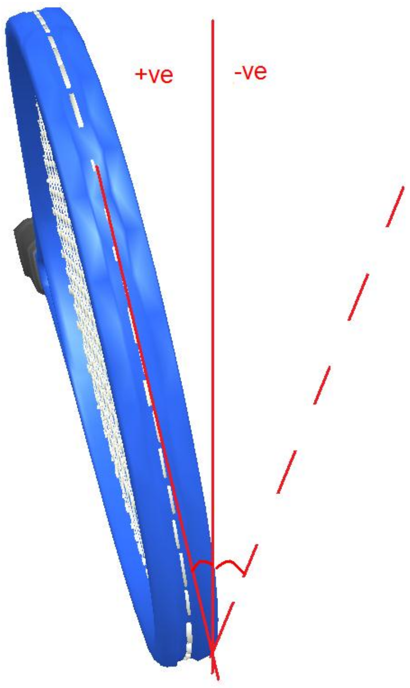


Figure 4.9 – Definition of the racket inclination angle. The orientation is shown for a backhand as viewed in Figure 4.2. The angle is taken from the vertical axis of the global coordinate system, as shown, with a closed racket-head orientation yielding a positive angle and an open inclination yielding a negative angle.

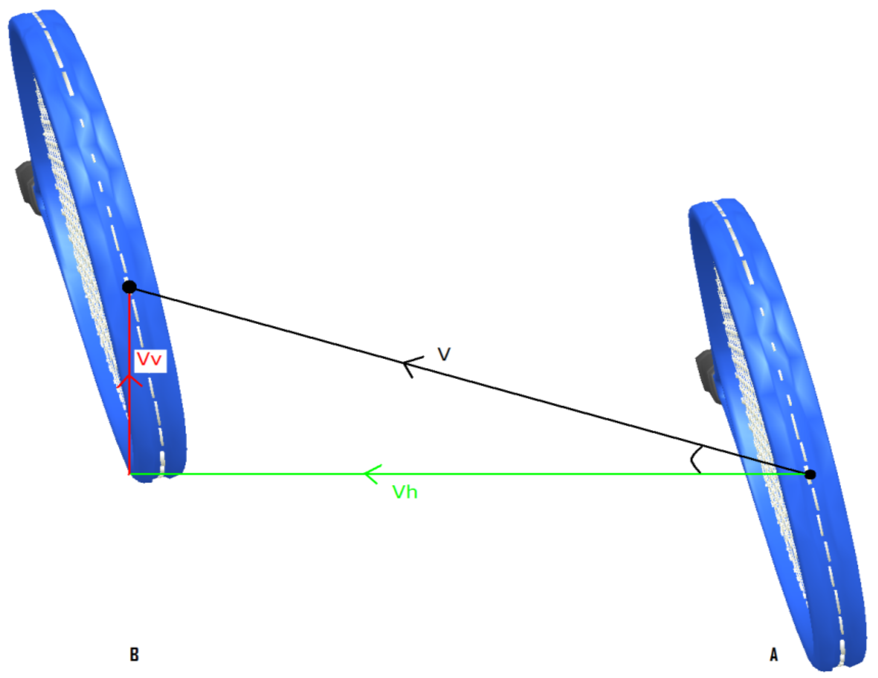


Figure 4.10 – Definition of the racket angle. The angle is derived from the instantaneous racket velocity components Vv and Vh, and is taken to the horizontal with respect to the vector 'V'. The orientation is shown for a backhand as viewed in Figure 4.2, travelling from position A to B.

The inclination of the racket was defined with respect to the vertical lab axis (Figure 4.9), with a closed racket-head inclination defined as a positive angle. The racket angle was defined as the angle to the horizontal, and was calculated from the instantaneous vertical and horizontal velocities of the racket with respect to the laboratory axes (Figure 4.10).

The duration of movement analysed was from the commencement of the forward swing of the racket to a point 20 frames past the point of racket and ball collision. The decision to retain data after ball impact was made to facilitate analysis of individual players. For example, a player might not produce a high amount of spin because an important factor occurred post-impact, rather than pre-impact. The commencement of the forward swing was determined by a positive change in the Y segment velocity of the racket, and was checked using the animation viewer in the software package. The analogue signal from the microphone was used to determine the event of racket-ball collision, and a further event created 20 frames after this event. The majority of analysis is concerned with the movement of joints in the time period leading up to, and including impact. However, the last event was created for the purposes of the case study analysis to establish whether key variables were only optimised after impact in some cases.

The high-speed video data was uploaded to specialist software (MotionScope M1.0.3, Redlake, USA). Footage where the tennis ball was not in shot was edited out and the file converted to an avi. format. The converted video was analysed using Human video digitising software (HMA Technology, Canada). The video footage was firstly scaled using a simple 0.5 m calibration square. The first usable twenty frames following racket-ball impact were then manually digitised using a line visible on the ball throughout the twenty frames (further details in 3.4). Whilst it was not always possible to digitise the first twenty frames following impact the straight line on the graph of angular change (Figure 4.11) indicates that there was typically no decay in the spin rate throughout this time period. If a line was not visible on the ball throughout the twenty frames then this data was discarded. The angular change of the ball over the twenty frames was then calculated, using the video analysis software, and presented in graphic form (Figure 4.11). The difference between the first and twentieth frames represented the spin over this time period.

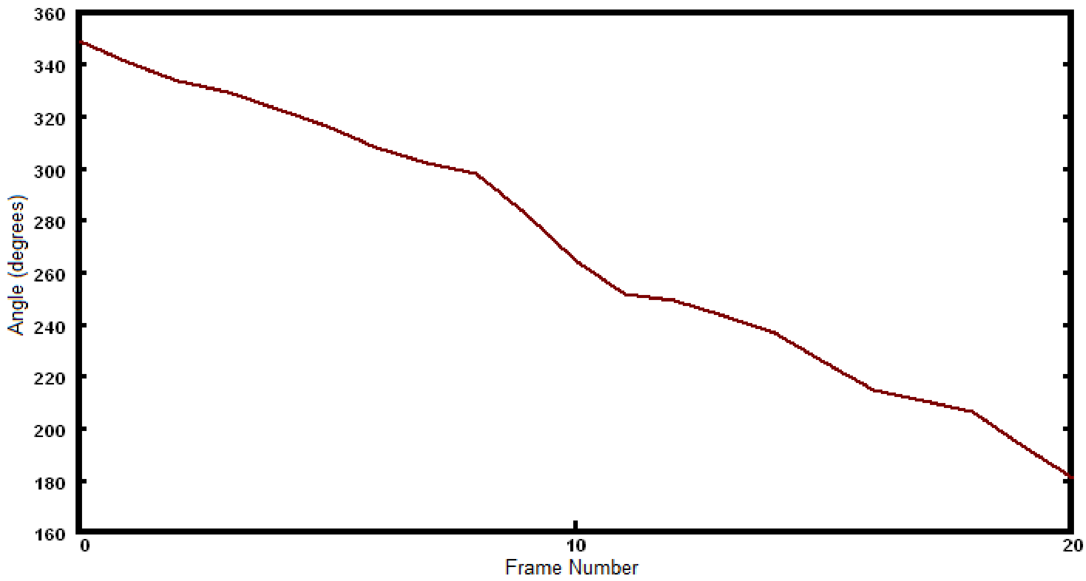


Figure 4.11 – Typical angular displacement of the Two-dimensional spin axis throughout the twenty frame collection period.

The repeatability of the digitisation process was examined by redigitising all trials twice more. A trial was accepted if the maximum difference between digitising attempts was either less than 10 %, or in some cases where the spin rate was low, less than 41.67 rev.min^{-1} (5° angular change). This is a comparable error rate to that of Kelley *et al.* (2008). This error acceptance would lead to a worst case scenario of 353.3 rev.min^{-1} for a spin rate of 3533.33 rev.min^{-1}, which has not been considered a large amount of ball spin. The reality was that most trials recorded less spin than the example above, and thus the error was well within this. Trials falling outside of this error acceptance were discarded. The mean of the three digitising trials were then exported into a spreadsheet (Excel 2007, Microsoft, USA), and the angular change was converted to revolutions prior to the calculation of the spin rate of the ball in rev.min^{-1} using the formulae presented below.

$$r = \frac{\theta}{360}$$

Where r is the number of ball revolutions and θ is the angular change in degrees.

$$\omega = \left(\frac{r}{t}\right) \times 60$$

Where ω is the spin rate in rev.min^{-1}, r is the number of ball revolutions and t is the elapsed time equal to 0.02 seconds. The multiplication factor of 60 converts the spin rate from rev.s^{-1} to rev.min^{-1}.

The calculated kinematic variables and ball spin rates were then exported into a statistical analysis package (PASW Statistics 18, IBM, USA). Specific details regarding the statistical analysis of this data can be found in their relevant chapter. Chapter 5 investigated the differences between flat and topspin strokes, chapter 6 determines the variables that relate to ball spin and chapter 7 investigates the findings of these chapters in relation to individual case studies.

5. KINEMATIC DIFFERENCES BETWEEN FLAT AND TOPSPIN TENNIS GROUNDSTROKES

5.1 INTRODUCTION

Previous analyses of tennis kinematics have identified some differences between the flat and topspin strokes. In the forehand stroke the differences were identified in racket kinematics, but the overall contribution of body segments to racket velocity was similar (Takahashi *et al*., 1996). There has not been a direct comparison of flat and topspin strokes made for the backhand groundstroke. The results presented in this chapter compare the kinematics of flat and topspin strokes for the forehand and backhand groundstrokes. In addition, the differences in the spin rate of the ball for each stroke are presented.

5.2 METHODS OF ANALYSIS

The methodology described here is specific to the analysis in this chapter. For details of the full methodology relating to the results outlined here please refer to the general methods in Chapter 4.

All twenty participants were selected for analysis. No formal sample size calculation was made, but this number is in excess of samples typically used in analyses of tennis groundstrokes (Knudson, 1990). The experimental design used was a within-participants design whereby a number of variables were compared for a flat and topspin stroke. This is a similar approach to that taken by Takahashi *et al.* (1996) in a previous analysis of topspin forehand strokes. The forward swing to ball impact was analysed for forehand and backhand strokes. The change in angular data was calculated during this time period, thus determining the net anatomical movement during the forward swing of each stroke, though not necessarily the direction of the movement at impact. For example, the arm might be abducting throughout the forward swing and then adduct prior to impact but the direction of the movement at the joint would be stated as abduction. This was the approach taken in previous analyses of tennis strokes (Takahashi *et al*., 1996; Elliott *et al*., 1997; Reid and Elliott, 2002), therefore allowing for comparison between the present investigation and these analyses. Joint velocities were recorded at ball impact, therefore the adduction at the shoulder in the previous example would be indicated by this measure. Segmental velocities were also recorded at ball impact, including that of the racket. The angles defined in relation to the racket are given previously (Chapter 4.4).

Calculated kinematic variables and the ball spin rates were exported into a statistical analysis package (PASW statistics, IBM, USA). Normality of each variable was assessed using the Kolmogorov-Smirnov test, which compares the distribution of scores observed and that expected of a normal distribution. In addition, 95% confidence intervals of the skewness and kurtosis of the data were also produced. The second measure was used because tests of normality, such as Kolmogorov-Smirnov, tend to be sensitive to larger sample sizes (Field, 2009). Therefore, variables were assumed to be normally distributed unless the Kolmogorov-Smirnov test found significant differences ($p < 0.05$) and one of the confidence intervals of skewness and kurtosis did not cross zero. If the 95% confidence interval of both these measures contained zero then the possibility remained that the distribution of scores could be normal.

Some variables were judged by the above criteria to be normally distributed. Differences in each of these variables were assessed by the means of a paired-samples t-test. The differences of variables deviating from a normal distribution were assessed using a Wilcoxon paired-samples test. The alpha level for each of these tests was set at 0.05.

5.3 RESULTS

5.3.1 FOREHAND

Participants produced larger amounts of ball spin ($t_{(82)} = -9.86$, $p < 0.001$, 95% CI of difference, 648.58-812.50) when playing the topspin forehand stroke (1518.66 $rev.min^{-1} \pm 709.54$) than the flat forehand stroke (761.13 $rev.min^{-1} \pm 579.95$). The kinematics of the racket (Table 5.1), angular change of the upper and lower extremity during the forward swing (Table 5.2) and their associated velocities (Table 5.3) are presented in turn.

Table 5.1 – Mean (SD) racket characteristics at impact.

	Flat Stroke	**Topspin Stroke**
Racket Velocity ($m.s^{-1}$)	18.43 (4.91) **	19.89 (3.82) **
Vertical Racket Velocity ($m.s^{-1}$)	5.16 (2.72) *	8.71 (2.82) *
Racket Inclination w.r.t. vertical (°)	1.22 (7.72) *	6.30 (7.93) *
Racket Angle w.r.t. horizontal (°)	19.50 (9.97) *	30.76 (9.73) *
Downward displacement of racket in forward swing (m)	0.37 (0.34) *	0.30 (0.39) *
Upward displacement of racket prior to impact (m)	0.12 (0.10) **	0.21 (0.11) **

*significant difference based on paired t-test, **significant difference based on Wilcoxon matched pairs. ($p < 0.05$)

Table 5.2 – Mean (SD) angular change (°) of kinematic rotations

Joint	**Action**	**Flat Stroke**	**Topspin Stroke**
Racket w.r.t. Forearm	Downward	7.18 (12.70)	9.28 (15.73)
Forearm rotation w.r.t. humerus	Supination	20.36 (22.09) *	24.73 (26.28) *
Elbow	Extension	7.97 (24.42)	8.95 (29.54)
Rotation of humerus w.r.t. trunk	Internal	45.69 (31.03) **	59.31 (31.82) **
Shoulder	Adduction	5.49 (14.80)	5.23 (16.24)
Hip	Extension	42.57 (20.42) *	50.45 (21.80) *
Knee	Extension	8.48 (16.29) *	15.47 (20.76) *

*significant difference based on paired t-test, **significant difference based on Wilcoxon matched pairs. ($p < 0.05$)

Table 5.3 – Mean (SD) linear ($m.s^{-1}$) and angular velocities ($°.s^{-1}$) at impact.

Joint	Action	Flat Stroke	Topspin Stroke
Forearm COM *	Upward	1.77 (0.68) *	2.61(0.93) *
Upper Arm COM *	Upward	0.92 (0.47) *	1.34 (0.60) *
Racket w.r.t. Forearm **	Downward	57.32 (585.45) **	-179.56 (670.59) **
Forearm w.r.t. humerus	Pronation	378.23 (268.27)	413.76 (285.00)
Elbow **	Flexion	60.60 (193.87) **	106.09 (195.76) **
Rotation of Humerus	Internal	180.19 (288.80)	208.08 (305.80)
Shoulder	Abduction	162.64 (155.58)	197.60 (134.23)
Hip *	Extension	45.45 (87.02) *	86.51 (182.05) *
Knee *	Flexion	62.25 (167.82) *	110.31 (214.52) *

*significant difference based on paired t-test, **significant difference based on Wilcoxon matched pairs. ($p < 0.05$)

The angular changes throughout the duration of the forward swing (Table 5.2) indicate the key joint rotations from the start of the forward swing to impact, but these rotations do not occur linearly throughout the forward swing. Figure 5.1 provides an example of how the rotations at the hip, shoulder and elbow typically vary throughout the forward swing of the forehand. The movement pattern presented provides an illustration of the key joint actions, but it should be noted that the magnitude and timing of these actions varies between participants.

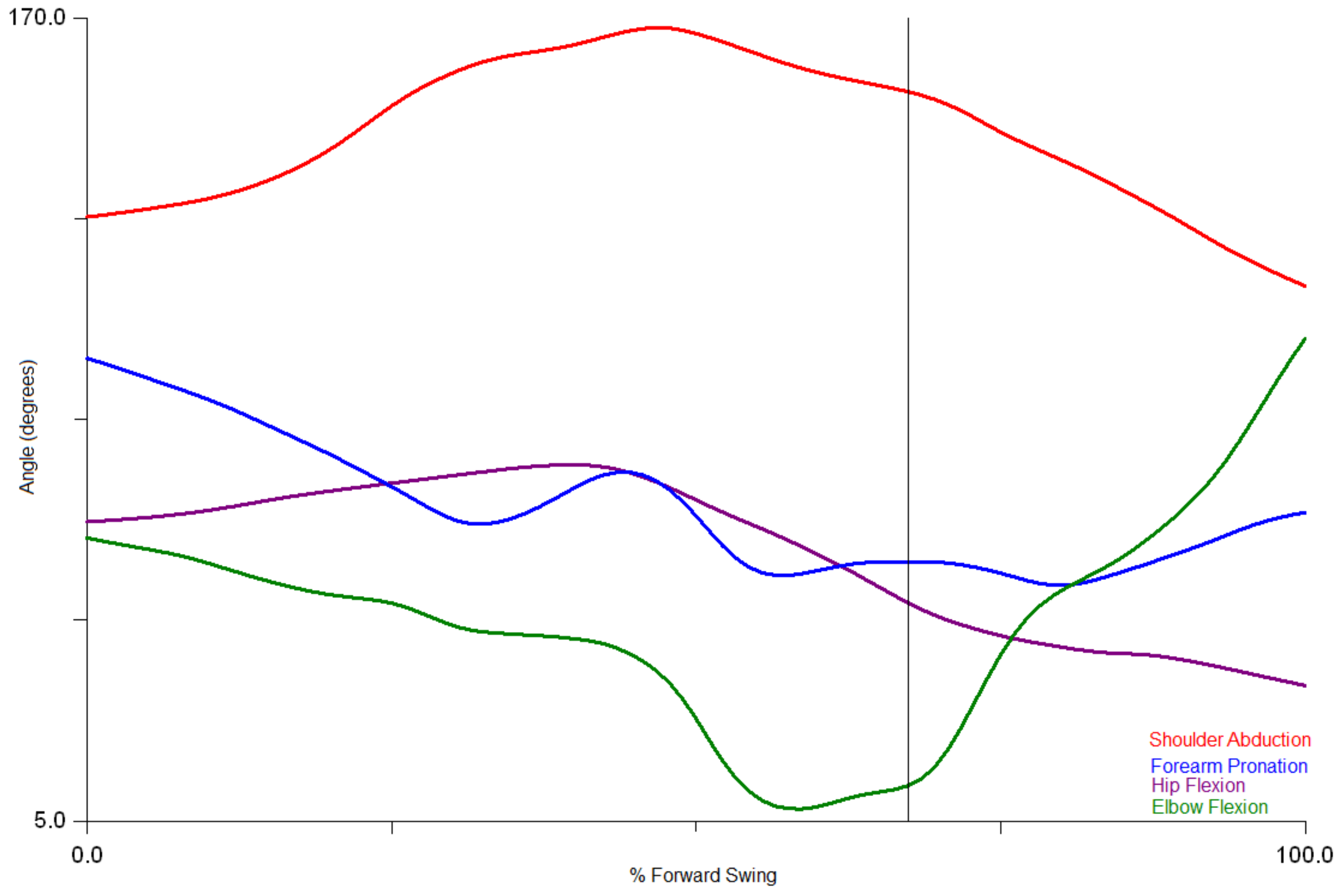


Figure 5.1 – Selected angular patterns throughout the forward swing of the forehand stroke of a single participant. Point of ball impact is represented by the solid vertical line.

5.3.2 BACKHAND

Participants produced larger amounts of ball spin ($Z = 7.23$, $p < 0.001$, 95% CI of difference, 565.58-843.80) when playing the topspin backhand stroke (1175.72 $rev.min^{-1}$ ± 658.88) than the flat backhand stroke (473.27 $rev.min^{-1}$ ± 522.14). The kinematics of the racket (Table 5.4), angular change of the upper and lower extremity during the forward swing (Table 5.5) and their associated velocities (Table 5.6) are presented in turn.

Table 5.4 - Mean (SD) racket characteristics at impact.

	Flat Stroke	**Topspin Stroke**
Racket Velocity ($m.s^{-1}$)	16.59 (3.82) *	17.06 (3.34) *
Vertical Racket Velocity ($m.s^{-1}$)	3.82 (2.35) *	7.11 (2.69) *
Racket Inclination w.r.t. vertical (°)	2.08 (6.16) *	5.84 (7.42) *
Racket Angle w.r.t. horizontal (°)	14.09 (10.44) *	25.83 (10.97) *
Downward displacement of racket in forward swing (m)	0.24 (0.40) **	0.11 (0.40) **
Upward displacement of racket prior to impact (m)	0.14 (0.13) **	0.24 (0.16) **

*significant difference based on paired t-test, **significant difference based on Wilcoxon matched pairs. ($p < 0.05$)

Table 5.5 – Mean (SD) angular change (°) of kinematic rotations.

Joint	**Action**	**Flat Stroke**	**Topspin Stroke**
Racket w.r.t. forearm	Upward	17.30 (10.48)	18.10 (10.96)
Forearm w.r.t. humerus	Supination	9.63 (18.78) **	12.63 (20.57) **
Elbow	Flexion	4.93 (28.39)	7.11 (32.27)
Rotation of humerus w.r.t. trunk	External	14.20 (11.27)	15.58 (11.62)
Shoulder	Abduction	9.99 (6.51)	9.73 (7.45)
Hip	Extension	21.56 (15.39) **	29.49 (16.43) **
Knee	Flexion	6.54 (18.37)	2.82 (21.62)

*significant difference based on paired t-test, **significant difference based on Wilcoxon matched pairs. ($p < 0.05$)

Table 5.6 – Mean (SD) linear ($m.s^{-1}$) and angular velocities ($°.s^{-1}$) at impact.

Joint	Action	Flat Stroke	Topspin Stroke
Forearm COM	Upward	1.54 (1.03) **	2.06 (0.97) **
Upper Arm COM	Upward	0.84 (0.64) **	1.03 (0.58) **
Racket w.r.t. forearm	Upward	61.21 (255.91)	86.26 (299.21)
Forearm w.r.t. humerus	Supination	374.52 (337.68)	416.90 (331.08)
Elbow	Flexion	93.03 (310.98) **	139.83 (335.69) **
Humerus Rotation w.r.t. trunk	External	260.93 (180.78)	264.03 (178.33)
Shoulder	Adduction	28.25 (173.06)	41.94 (156.93)
Hip	Extension	100.60 (107.74)	104.81 (98.17)
Knee	Flexion	93.28 (102.46)	92.62 (127.20)

*significant difference based on paired t-test, **significant difference based on Wilcoxon matched pairs. ($p < 0.05$)

The angular changes throughout the duration of the forward swing (Table 5.5) indicate the key joint rotations from the start of the forward swing to impact, but these rotations do not occur linearly throughout the forward swing. Figure 5.2 provides an example of how the rotations at the hip, shoulder and elbow typically vary throughout the forward swing of the double-handed backhand. The movement pattern presented provides an illustration of the key joint actions, but it should be noted that the magnitude and timing of these actions varies between participants.

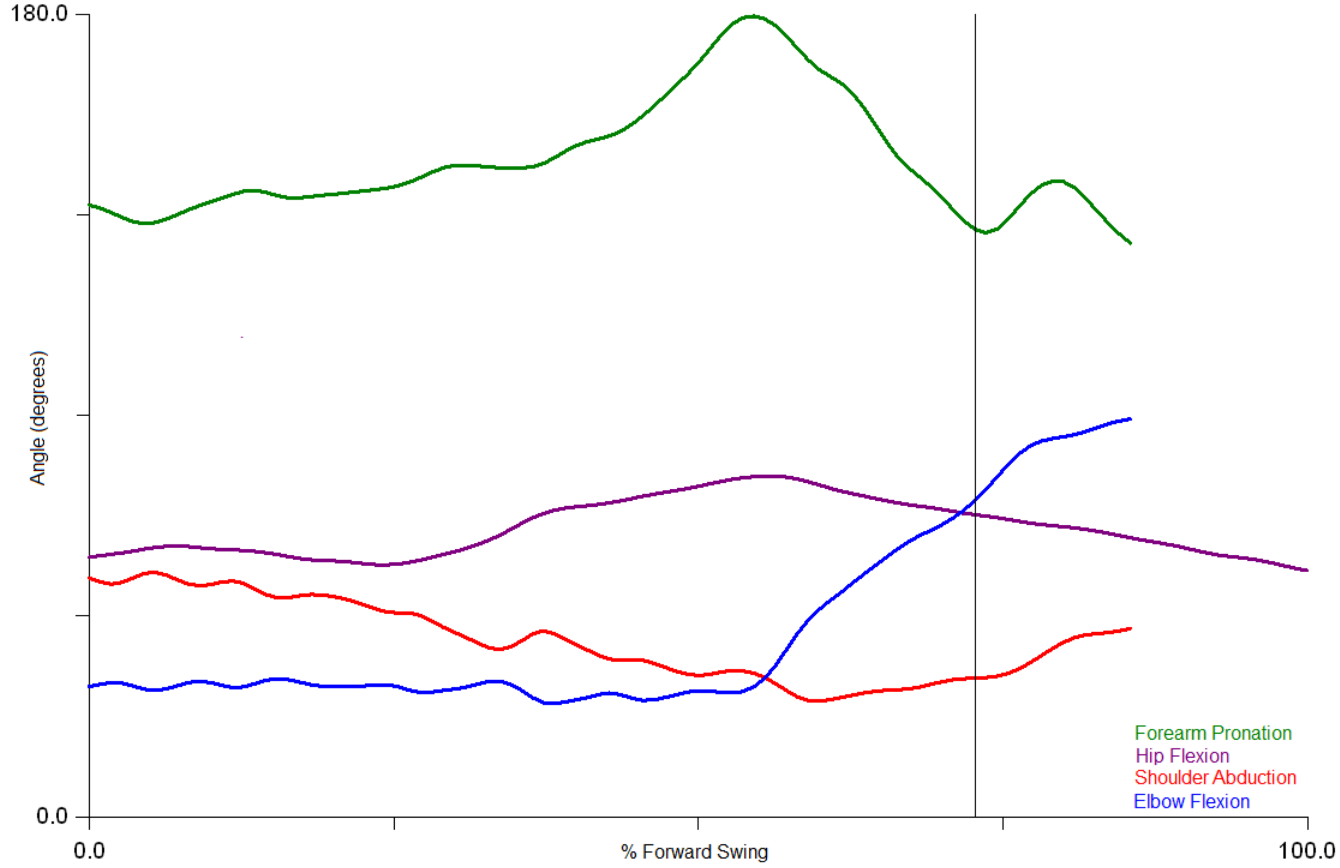


Figure 5.2 - Selected angular patterns throughout the forward swing of a double-handed backhand stroke of a single participant. Point of ball impact is represented by the solid vertical line.

5.4 DISCUSSION

The purpose of the analysis here was to establish whether the participants in the current study used a different strategy, reflected in their kinematics, when playing a topspin stroke compared to a flat stroke. Clear differences were observed in the spin generated for the two stroke types, and these differences were accompanied by alterations in racket kinematics, and that of the player.

Participants produced significantly greater ball spin when playing the topspin stroke than when playing the flat stroke, for forehand and backhand strokes. When participants were asked to play with topspin, they produced 1518.66 $rev.min^{-1}$ (SD: 709.54; Range: 3504.17) for the forehand and 1175.72 $rev.min^{-1}$ (SD: 658.88; Range: 2775.00) for the backhand. These results appear to be in agreement with the limited studies that have reported ball spin rates, with the mean values corresponding to that of the professionals at the lower end of the analysis of Pallis (1997). The sizeable standard deviation of each stroke also indicates that some participants in the current study were capable of producing far more spin than the mean value. Indeed, some spin rates in excess of 3000 $rev.min^{-1}$ were recorded, which was in the range of the professional players recorded by Pallis (1997), and the maximum values reported by Kelley *et al*. (2008) and Goodwill *et al*. (2007).

The amount of ball spin produced when players were asked to hit a flat stroke was 761.13 $rev.min^{-1}$ (SD: 579.95; Range: 2820.83) for the forehand and 473.27 $rev.min^{-1}$ (SD: 522.14; Range: 3020.83) for the backhand. Spin rates for flat strokes have not been explicitly reported previously. However, these values are below the lower end of the values reported by Pallis (1997) when analysing professional players, perhaps indicating that professional players produce a reasonable amount of spin even when hitting a flat stroke.

The mean spin rates were larger in the forehand stroke than in the backhand, both when attempting to play with topspin and when hitting a flatter delivery. This is consistent with the work of Pallis (1997), Goodwill *et al*. (2007) and Kelley *et al*. (2008) and may indicate that it is more difficult to generate topspin on the backhand. The discussion that follows will analyse the forehand and backhand strokes in turn.

The results presented are indicative of a cohort as a whole that generates modest amounts of topspin, but within it there are individuals capable of creating values of a capable professional player. It is important that the reader is aware of this when comparing these results to previous kinematic analyses of tennis groundstrokes. The previous kinematic analyses have not reported values of ball spin, and have used tennis players from a wide range of ability levels. This should also be considered when placing the current results into context.

5.4.1 FOREHAND

The differences in the spin rates in the flat and topspin forehand strokes were accompanied by alterations in the kinematics of the racket and the human.

The racket velocity (19.22 ± 4.41 $m.s^{-1}$) was less than that recorded by Knudson and Blackwell (2005) in an analysis of advanced players, but within the range of 16.1-21.2 $m.s^{-1}$ previously reported in analyses of intermediate players (Knudson and Bahamonde, 1999; Blackwell and Knudson, 2005). Interestingly, the velocity was slightly higher for the topspin stroke (19.89 ± 3.82 $m.s^{-1}$) than the flat stroke (18.43 ± 4.91 $m.s^{-1}$), which may reflect a preference for playing the topspin stroke for most of the players in the cohort. Takahashi *et al*. (1996) did not report the velocity vector of the racket for the different types of topspin stroke, but they did observe an increase in the vertical velocity of the racket when playing the topspin stroke. This was also the case in the present study, with a vertical velocity of 5.16 ± 2.72 $m.s^{-1}$ when hitting a flat stroke and 8.71 ± 2.82 $m.s^{-1}$ when playing with topspin ($p < 0.001$, 95% CI of difference, 3.02-4.18). These values reflect a similar trend to that of Takahashi *et al*. (1996) and Elliott *et al*. (1997), though to a lesser magnitude.

The inclination of the racket head with respect to the vertical at ball impact was closed by an angle of 1.22 ± 7.72° for the flat stroke, and 6.30 ± 7.93° for the topspin stroke. These angles are indicative of the near vertical position of the racket-head identified by Knudson (1991) as an important factor in topspin production and are within the range of 1.1 to 7.4° identified in previous analyses of topspin groundstrokes (Blackwell and Knudson, 2005; Elliott and Marsh, 1989; Elliott *et al*., 1989a; Takahashi *et al*., 1996). The inclinations for both strokes in the present study are within the ranges identified previously for the production of topspin, but the significant effect ($p < 0.001$, 95% CI of difference, 4.18-7.12) may indicate that the slightly more closed end of this angular range is more conducive to topspin production. Takahashi *et al*. (1996) also observed this trend, but with a smaller difference between the two strokes. The present study and that previously identified through performance analysis, all fall below the optimal inclination of 9.7° identified by Groppel *et al*. (1983). What is clear from the present study is that players prefer a more closed racket position at impact when imparting topspin, but the importance of the magnitude of this movement is not established.

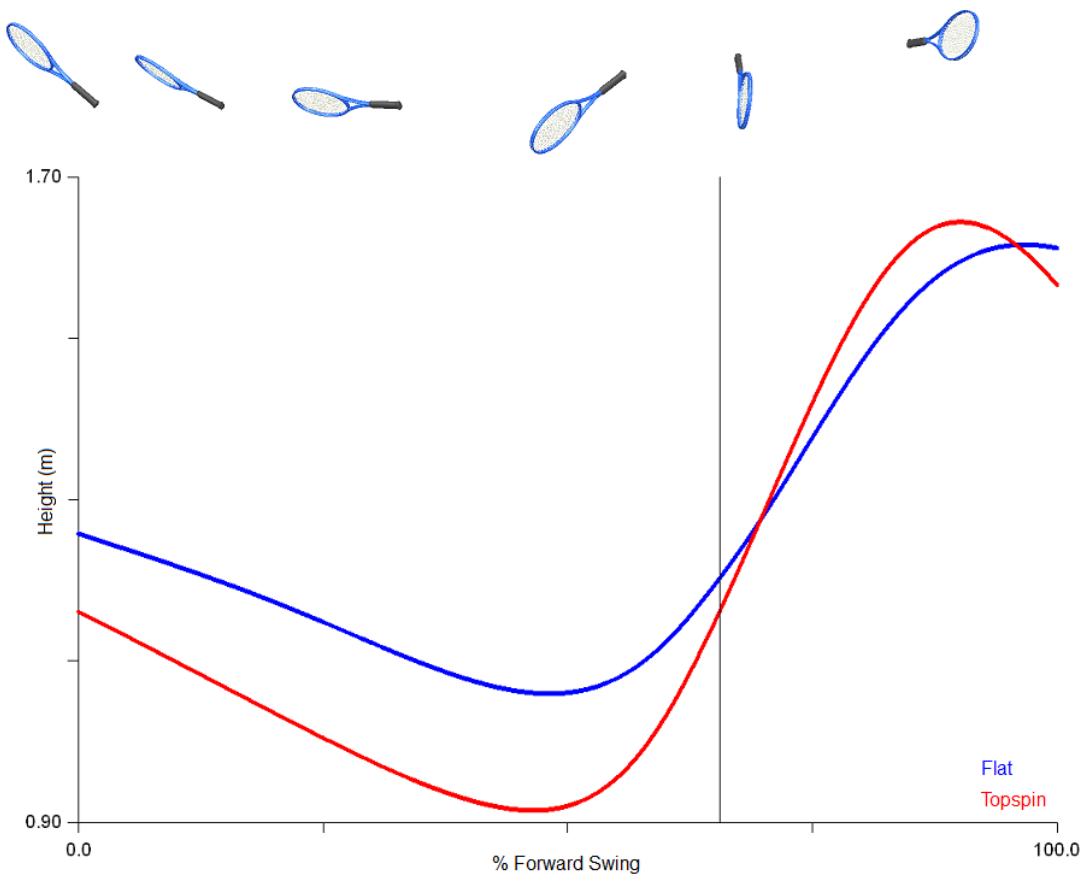


Figure 5.3 – Trajectory of the racket during a forehand stroke viewed perpendicular to the direction of the stroke.

The trajectory of the racket during the forward swing reflects overall movement of the racket from a high position at the start of the forward swing to a lower position at impact (Figure 5.3). There is variation in this measure however due to players moving the racket upwards throughout the forward swing. Regardless of the overall racket swing, participants moved the racket upwards in the later phase of the forward swing just prior to ball impact. The extent of this late upward movement was 0.12 m in the flat stroke, and 0.21 m in the topspin stroke. The increased upward movement has previously been identified as a critical factor when imparting topspin. Knudson (1991) identified the ideal path of the racket to be at an angle 28° to the horizontal, whilst angles from 17-47° have been calculated experimentally (Elliott and Marsh, 1989; Elliott *et al*., 1989a). The variance in this measure may be a function of the timing of this upward movement. Elliott *et al*. (1989a) suggested that players align the racket and ball prior to the upward movement, imparting an off-centre force to the ball. Later execution of this upward movement would be reflected by a larger angle between the racket path and the horizontal, near ball impact. The mean angle of the racket to the horizontal at the point of ball impact in the present study was 19.50° in the flat stroke and 30.76° in the topspin stroke. This suggests that the players in the present study positioned the racket below the ball prior to impact, before executing a rapid upward movement. The increased vertical velocity of the racket at impact and increased upward displacement prior to impact in the topspin stroke supports this.

To achieve the alterations in racket kinematics from the flat stroke to the topspin stroke it makes intuitive sense to expect alterations in the kinematics of the player. A number of these adaptations were observed in the forehand stroke, primarily at the wrist and elbow but also in the lower limb. To achieve the low-to-high racket trajectory and accompanying large vertical velocity of the racket observed in the racket kinematics, adaptations are made by more proximal body segments. These actions could be achieved through movement of the upper limb as a single unit or the combination of the upper arm and forearm, more proximally, upward motion can also be driven by extension of the lower limbs during the forward swing. Differences ($p < 0.050$) between the flat and topspin forehand strokes were found in the kinematics of the forearm and elbow, but also at the hip and knee.

The vertical velocity of the racket with respect to the forearm altered from a downward velocity in the flat stroke, to an upward velocity in the topspin stroke (Flat 57.32 ± 585.45°s^{-1}, Topspin -179.56 ± 670.59°.s^{-1}), though there was no alteration in the angular change throughout the forward swing of the stroke. The relative motion of the racket and forearm is mainly downwards throughout the forward swing for both types of stroke, with the racket often travelling from a high position in the backswing to a lower position in the forward swing before an upward movement towards ball impact. The kinematics of the wrist in the present study was not measured directly, but by the relative motion of the racket and forearm (Chapter 4.4), so it is difficult to compare this to previous studies. Furthermore, this does not relate to a specific motion of the wrist, due to subtle changes in grip. For example, for a player with an eastern grip, upward motion of the racket with respect to the forearm would be as a result of radial deviation, whereas for a player with a western grip the same end result would be achieved through flexion at the wrist. The majority of players in the present study used a western or semi-western grip, but subtle changes in grip from player to player will result in the same movement being executed from a different anatomical rotation. Elliott *et al*. (1997) recorded a mean radial deviation of 7.4° for players with an eastern grip when playing a topspin stroke, contributing 19.2% of the racket velocity at ball impact. In the western group 10.8° of wrist flexion contributed to 22.9 % of the velocity at impact. The results of this, and the present study indicate that the magnitude of the motion may not be an important factor in topspin strokes, but the rate at which it is executed may be. The potential importance of this movement is investigated in the next chapter (Chapter 6).

The vertical velocity of the forearm was significantly greater ($p < 0.001$) in the topspin stroke (2.61 ± 0.93 m.s^{-1}) than in the flat stroke (1.77 ± 0.68 m.s^{-1}), and the same trend was observed for the humerus (Flat: 0.92 ± 0.47 m.s^{-1}; Spin: 1.34 ± 0.60 m.s^{-1})($p < 0.001$, 95% CI of difference, 0.62-0.98). These segmental velocities are not a measure previously calculated in this way, but do potentially explain the increase in the vertical velocity of the racket, perhaps in conjunction with movement of the hand. Interestingly, the velocity of the forearm is greater than that of the humerus, irrespective of the type of stroke, indicative of an increase in the vertical segment velocities towards the distal point of the chain. It may also show that the forearm moves independently of the upper arm during the forward swing of the stroke.

The nature of the relative movement between the forearm and upper arm is characterised by two types of forward swing. One technique was characterised by the upper limb moving into a relatively adducted position adjacent to the trunk during the course of the forward swing, before abducting towards ball impact whilst the arm extended at the elbow before flexing prior to ball impact (Figure 5.1; Technique A - Figure 5.4). The other technique was characterised by a more abducted position of the shoulder at the beginning of the forward swing that became more adducted throughout the stroke, with a similar pattern of extension, but then a lesser amount of flexion at the elbow (Technique B – Figure 5.4). The nature of these patterns appeared to remain the same regardless of the type of stroke played, and therefore no differences were observed in shoulder abduction or elbow flexion between the two stroke types. The abduction of the upper arm at the shoulder is an anatomical rotation that has not previously been isolated, though Elliott and co-workers (1996, 1997) established that a combination of forward elevation and abduction did not alter between a flat and topspin stroke. The patterns found at the elbow are similar to that by Elliott *et al*. (1989a), who established that the more modern forehand was characterised by a larger elbow flexion and angular velocity immediately prior to ball impact, in contrast to the more traditional stroke pattern. That the amount of elbow extension throughout the forward swing, and the elbow flexion velocity at impact falls between the two group means in the Elliott *et al*. (1989a) study, indicates that participants in the present study use each of these types of technique. Interestingly, a difference in elbow flexion velocity was found in the present study between the flat (60.60 ± 193.87°.s^{-1}) and topspin (106.09 ± 195.76°.s^{-1}) strokes. If an upward movement of the racket is a key component of producing topspin then rapid elbow flexion would be beneficial in driving this motion, particularly for players with a semi-western or western grip. It might also follow that the former technique identified here (A – Figure 5.4), and the multi-segment technique identified previously (Elliott *et al*. (1989a) may be more conducive to producing this movement.

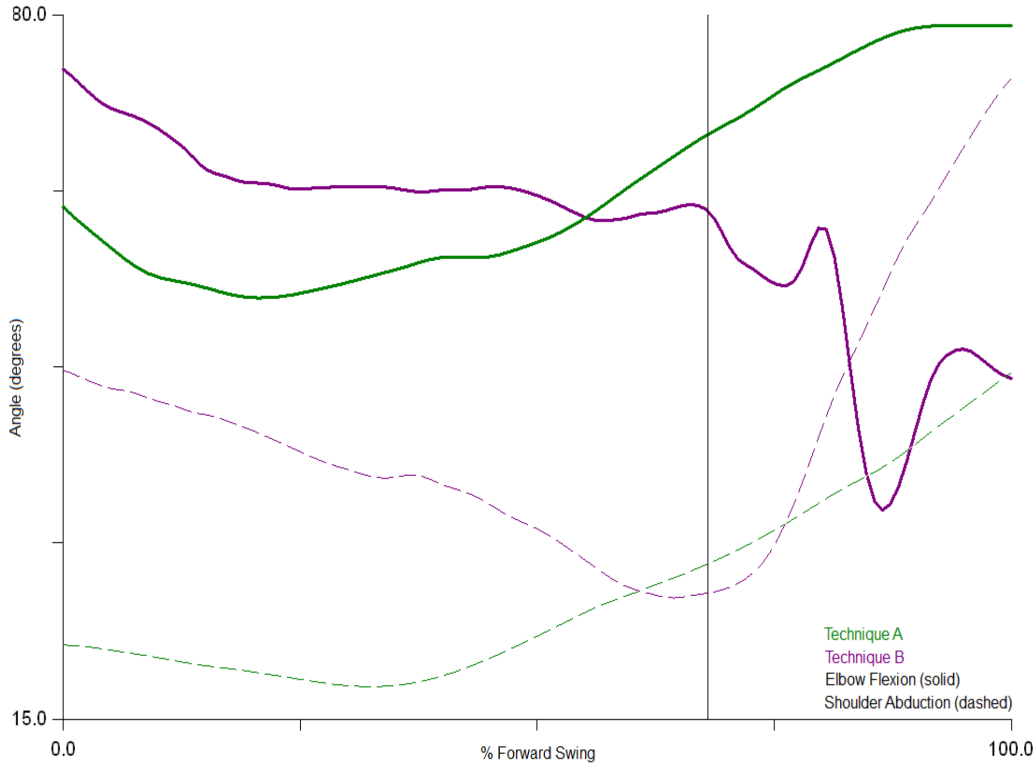


Figure 5.4 – Types of forehand swing characterised by contrasting patterns of elbow flexion-extension and shoulder abduction-adduction. Point of ball impact is represented by solid vertical line.

Regardless of the movement pattern of the upper limb during the forward swing, larger angular changes were identified in the topspin stroke ($p < 0.001$, 95% CI of difference, 8.56-19.91) for internal rotation of the upper arm. The reason for the increased internal rotation in the topspin stroke (Flat 45.69 ±31.03°; Spin 59.32 ± 31.82°) is difficult to ascertain, due to the different types of swing mechanics within the cohort, but does seem indicative of a greater swing. Similar angular changes were also recorded by Takahashi *et al*. (1996), but with up to 8° less motion in the topspin stroke. An extension of that work revealed a reduced level of internal rotation in players using the eastern racket grip (Elliott *et al*., 1997), and in that case there was more rotation in the topspin stroke. As specific groupings for racket grip were not identified in the present study, this may go some way to revealing the variability in the measures presented here. The angular velocity of the internal rotation was 195.40°.s^{-1} for both groups, some way below the mean of 873.63°.s^{-1} previously observed for a flat stroke (Takahashi *et al*., 1996). The precision of the measurement obtained by Takahashi *et al*. (1996) may be questioned due to the marker set used in that study. Nonetheless, they found this rotation to contribute between 39.9 and 53.6% of the forward and upward velocity of the racket at ball impact, and therefore the difference in the angular velocity of this and the present study may explain the larger racket velocity found by Takahashi *et al*. (1996).

A small, but significant difference ($p = 0.027$) was observed in the pronatory-supinatory motion of the forearm between the two types of stroke, accompanied by a non-significant difference in the angular velocity of this movement ($p = 0.053$). The forearm largely supinates throughout the forward swing before pronating prior to ball impact (Figure 5.1), similar to the pattern observed with extension then flexion at the elbow. This pronatory motion may be important in adjusting the racket-head to the correct inclination prior to impact, which may explain the increase in angular velocities between flat (378.23 ± 268.27°.s^{-1}) and topspin (413.76 ± 285.00°.s^{-1}) in order to make this adjustment. These measures have seldom been reported previously, perhaps due to the belief that the movement has limited value. Takahashi *et al*. (1996) demonstrated that forearm pronation contributes little to racket-head velocity at the point of ball impact, whilst Knudson's (1991) guidelines for producing topspin stated that the supposed benefits of this action in producing topspin were a fallacy. The modest differences between the flat and the topspin stroke here may indicate that this is the case, but the greater angular velocity here compared to the 11.42°.s^{-1} reported by Takahashi *et al*. (1996) for the topspin stroke suggests it may have a more important role in the strokes of the players in this cohort.

In addition to the kinematic alterations between the two strokes in the upper limb, the differences in racket kinematics, may be affected by the adaptations in the lower limb. There was greater extension of the hip (Flat: 42.57 ± 20.42°; Spin: 50.45 ± 21.80°) and the knee (Flat: 8.48 ± 16.29°; Spin: 15.47 ± 20.76°) for the topspin stroke in the present study. A comparison of these measures for different types of forehand strokes has not previously been reported, but the values are largely in agreement with Iino and Kojima (2003) for the hip (49.4°), and slightly less for the knee (29.6°), but generally more than the study of Elliott *et al*. (1989a) who recorded a maximum extension of 29.7° for the hip and 11.4° at the knee. The difference between the Elliott *et al*. (1989a) study and the more recent results may reflect a changing trend in the role of the lower limb in the modern tennis forehand. Modern forehand strokes are often hit from an open stance, which is generally accompanied by greater extension of the lower limbs (Crespo and Higueras, 2001). The increased extension in the present study was also accompanied by modest increases in the angular velocity of the hip ($p = 0.024$) and the knee ($p = 0.028$). This may help to increase the upward velocity of the upper limb and the racket, though the precise benefit is difficult to ascertain due to a large variation between participants in this measure.

5.4.2 BACKHAND

The increased spin rate for the topspin stroke was accompanied by alterations in racket kinematics, and some differences in the upper and lower limb kinematics of the players. Generally these kinematic differences between the flat and topspin strokes were not of the same magnitude as that observed in the forehand stroke. The reason for this may be, in part, due to the lower ball spin rate for each topspin condition, and a larger variability due to some players using a single-handed and others using a double-handed grip.

The resultant velocity of the racket of 16.59 ± 3.82 m.s^{-1} for the flat stroke and 17.06 ± 3.34 m.s^{-1} for the topspin stroke was comparable to the 18.8 m.s^{-1} recorded by Akutagawa and Kojima (2005) for a similar topspin stroke. However, the more recent study of Reid and Elliott (2002) recorded values of 25.42 m.s^{-1} for a single-handed, and 26.62 m.s^{-1} for a double-handed backhand stroke. The greater resultant racket velocity in that study was reflected in the magnitude of the vertical racket velocity. The present study found a greater vertical racket velocity ($p < 0.001$, 95% CI of difference, 2.62-3.14) in the topspin stroke (7.11 ± 2.69 m.s^{-1}) than the flat stroke (3.82 ± 2.35 m.s^{-1}). A similar trend was found by Reid and Elliott (2002), but with a vertical velocity of 16.0 m.s^{-1} for a double-handed topspin backhand, and 8.2 m.s^{-1} for the flat stroke with the same grip. The reason for the disparity in the magnitudes of the velocities in this study, and the findings of Reid and Elliott (2002) are, in part due to the position on the racket from which velocity was calculated, and ability differences. However, both studies have shown that players increase the vertical velocity of the racket at the point of ball impact when playing a topspin backhand stroke.

The orientation of the racket-head with respect to the vertical at the point of ball impact was found to be more closed for the topspin stroke (5.84 ± 7.42°) than the flat stroke (2.08 ± 6.16°) ($P < 0.001$, 95% CI of difference, 2.02-5.27). A similar trend was observed by Reid and Elliott (2002). The players in that study contacted the ball with an open racket face between 3.1-6.2° in the flat stroke and a closed orientation of 0.9-1.3° in the topspin stroke, depending on grip. The larger angular displacements from the vertical in both conditions were observed for players with a single-handed grip. The orientation of the racket, for both grips, was more closed in the present study and even more so for the double-handed grip. The mean inclination for the double-handed grip (7.92°) is similar to the suggestion of Knudson (1991) for the forehand stroke. No specific recommendations for racket inclination have been made for the backhand stroke, but it seems likely that similar combinations of optimal factors will be as likely to produce spin in the backhand as the forehand.

Irrespective of grip, the participants moved the racket from a high position at the commencement of the forward swing, to a lower position at ball impact. Although this was the general trend in the racket path, this initial move downwards was followed by movement upwards prior to impact, in a similar pattern to the forehand (Figure 5.3). The range of this movement was 0.14 m in the flat stroke, but 0.24 m in the topspin stroke, suggesting that the racket is placed further below the ball prior to impact in the topspin stroke. The extent of this upward movement has not previously been quantified, but has been identified as a desirable factor in the production of topspin in the backhand stroke (Elliott *et al.*, 1989b). The timing of this movement in the present study was immediately prior to impact, and this appears to be the case with the study of Elliott *et al*. (1989b) where the angle between the racket and the horizontal increased from 19° to 44° 0.005s before impact. A significant difference ($p < 0.001$, 95% CI of difference, 8.94-13.69) was observed in the present study in the angle of the racket to the horizontal between the flat (14.09°) and topspin (25.83°) strokes. This steeper trajectory at impact in the topspin stroke, along with the increased upward movement of the racket, suggests that the upward movement occurs late in both strokes but to a greater extent in the topspin stroke. This results in a larger vertical racket velocity at ball impact.

The increased vertical velocity of the racket and the more closed position of the racket-head at impact in the topspin stroke will be the result of adjustments by more proximal body segments. In the upper limb, differences between the two strokes ($p < 0.001$) were found in the forearm kinematics and the vertical velocities of the forearm and the upper arm. The nature of these differences depended on the type of backhand stroke played.

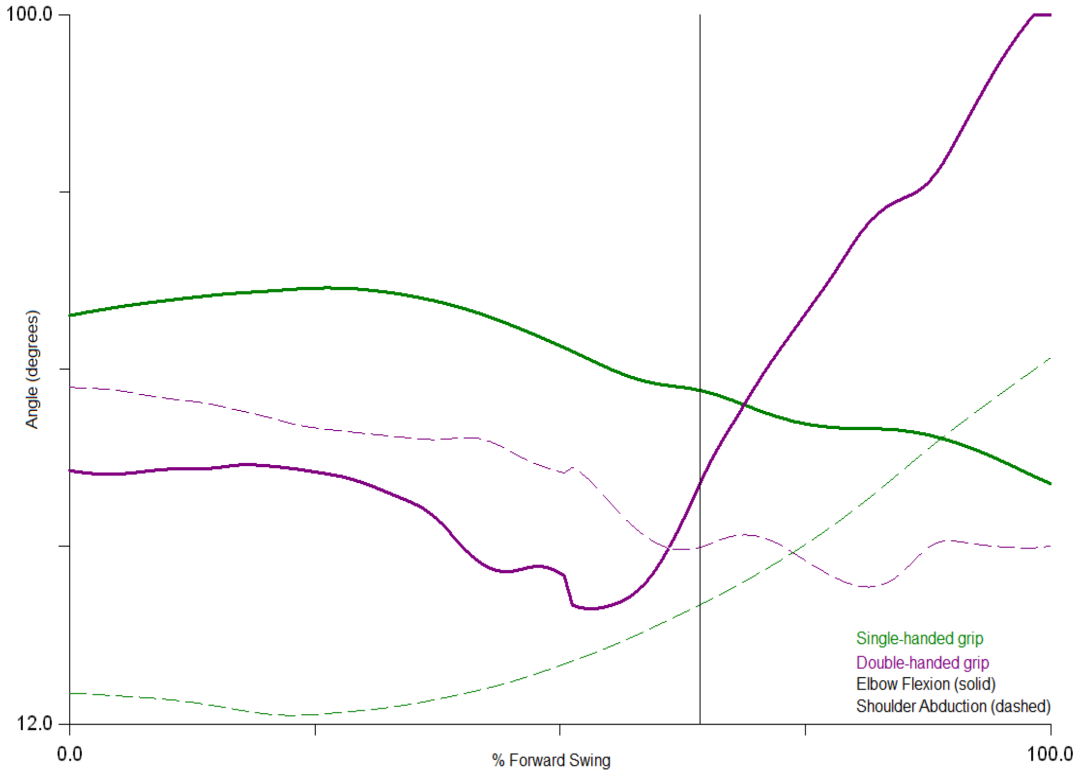


Figure 5.5 – Comparison of single- and double-handed techniques shown through contrasting patterns of elbow flexion-extension and shoulder abduction-adduction. Point of ball impact is represented by solid vertical line.

Regardless of backhand technique, the participants increased the vertical velocity of the upper arm (Flat 0.84 ± 0.64 $m.s^{-1}$; Topspin 1.03 ± 0.58 $m.s^{-1}$) and forearm (Flat 1.54 ± 1.03 $m.s^{-1}$; Topspin 2.06 ± 0.97 $m.s^{-1}$) when playing the topspin stroke. This increased velocity is likely to contribute to the increased vertical velocity of the racket at ball impact, believed to be a key mechanism for producing topspin (Groppel *et al.*, 1983). The means by which this increased velocity was achieved varied between the single- and double-handed grips. The participants using the single-handed grip extended the forearm at the elbow through the forward swing and continued to abduct the upper arm at the shoulder to ball impact. Contrarily, participants using the double-handed grip used elbow flexion to elevate the racket in the later stages of the forward swing whilst keeping a more adducted position of the upper arm (Figure 5.5). Neither of these rotations altered significantly between the flat and topspin strokes, suggesting that this movement pattern remained similar irrespective of technique. This pattern is consistent with the findings of Reid and Elliott (2002) for their comparison of the two grips across a number of backhand stroke types. However, the rate of elbow flexion did increase from $93.03°.s^{-1}$ in the flat stroke to $139.83°.s^{-1}$ in the topspin stroke, with the participants with a double-handed grip flexing the forearm at $358.84°.s^{-1}$. This has not been previously recorded, but may indicate that the double-handed grip enables participants to quickly elevate the racket prior to ball impact, thus making it advantageous for producing topspin. The comparison of ball spin rates between the two types of grip supports this (Single-handed 940.44 ± 720.68 $rev.min^{-1}$; Double-handed 1309.20 ± 591.43 $rev.min^{-1}$), however the small sample size and the low mean spin rate for both groups suggest that this should be interpreted with caution.

Whilst many of the upper limb rotations differed between the types of grip, the forearm did supinate in a similar manner throughout the forward swing to ensure the correct positioning of the racket-head at the point of ball impact (Figure 5.2). The 3° mean increase of supination in the topspin stroke indicates that this was used to ensure a more closed racket-head inclination (Figure 4.9), as this increased by a similar amount.

The extension of the hip is the primary lower limb action responsible for elevating the player throughout the forward swing, regardless of stroke or grip type. Participants varied in the use of knee action, but this often flexed late in the forward swing once the centre of gravity of the player had been transferred towards the ball. This mechanism was also observed by Kawasaki *et al*. (2005). The key alteration in the topspin stroke was increased extension of the hip throughout the forward swing, however this was not accompanied by an increase in the rate of extension. This suggests that the lower limb might be responsible for raising the racket from a lower trajectory in the topspin stroke, but the action of the upper limbs were responsible for increasing the upward velocity of the racket-head.

5.5 SUMMARY OF RESULTS

This chapter has identified differences in the kinematics of the racket and the player when playing flat and topspin groundstrokes (Table 5.7). What these differences show us, is that players adapt their stroke technique when imparting topspin in comparison with a flatter stroke. However, these results do not identify which of these differences are most important in the production of topspin. Furthermore, each variable is accompanied by significant variation, not least of the spin rate itself, indicative of an open skill, and a number of participants with different techniques. The chapters following this one attempt to address these areas.

Chapter 6 identifies the kinematic variables most associated with the spin rate of the ball. Following this, Chapter 7 analyses individual cases of good performance in an attempt to identify a technique, or a number of techniques, that successfully produce high amounts of ball spin.

The results of each of these chapters are then discussed (Chapter 8) to summarise the key findings.

Table 5.7 – Summary of significant differences between flat and topspin groundstrokes.

	Forehand	**Backhand**
Ball Spin	✓	✓
Vertical Racket Velocity	✓	✓
Racket Inclination	✓	✓
Racket Trajectory	✓	✓
Racket Velocity	✓	✓
Racket Angle at Impact	✓	✓
Racket w.r.t forearm	✗	✗
Racket w.r.t forearm velocity	✓	✗
Vertical Forearm Velocity	✓	✓
Forearm Pronation-Supination	✓	✓
Forearm Pronation-Supination Velocity	✗	✗
Elbow Flexion-Extension	✗	✗
Elbow Flexion-Extension Velocity	✓	✓
Axial Rotation Upper Arm	✓	✗
Upper Arm Rotation Velocity	✗	✗
Shoulder Abduction-Adduction	✗	✗
Shoulder Abduction-Adduction Velocity	✗	✗
Upper Arm Vertical Velocity	✓	✓
Hip Flexion-Extension	✓	✓
Hip Flexion-Extension Velocity	✗	✗
Knee Flexion-Extension	✓	✗
Knee Flexion-Extension Velocity	✗	✗

6. INVESTIGATION OF THE RELATIONSHIP BETWEEN BALL SPIN AND KINEMATICS

6.1 INTRODUCTION

The previous chapter identified the kinematic differences between flat and topspin strokes for the forehand and backhand. The adjustments in stroke mechanics between the flat and topspin strokes were similar to those found by previous analyses, but this information does not provide a full insight into which factors are largely responsible for the production of ball spin. Many authors have based their work on the recommendations made by Groppel *et al*. (1983) whose study validated an equation for producing ball spin based on a number of factors, mainly at the racket, based on the spin produced by a single participant playing a topspin forehand. The equation was found to predict ball spin accurately for the majority of trials, though not all. The validity of the factors in the equation may no longer be as relevant to the modern game, due to developments in racket technology and increasing complexity of tennis strokes. Thus, the sample size and stroke mechanics in that study limit the inference of these results to the modern game. The intention of this chapter is to establish which kinematic variables are the best predictors of ball spin.

6.2 METHOD OF ANALYSIS

The methods described here are specific to the analysis in this chapter. For details of the full methods relating to the results outlined here please refer to the methods in Chapter 4.

Calculated kinematic variables and the ball spin rates were exported into a statistical analysis package (PASW statistics, IBM, USA). Multiple regression models were created to determine which variables, or combination of variables, best predicts ball spin. The previous chapter revealed a number of significant ($p < 0.05$) adjustments between the flat and topspin groundstrokes, and some adjustments that were close to statistical significance that may be important. Entering a large number of variables into a regression model can result in the model being extremely difficult to interpret, often due to the shared variation between predictors (Field, 2009). Four regression models, each designed to answer a specific question, were created as a solution to this issue (Table 6.1 and 6.2). Model A was a prediction of ball spin from racket kinematics, Model B was a prediction of ball spin based on human kinematics and Model C was a prediction of ball spin from the strongest predictors from the first two models. It was hypothesised that the racket kinematics would be the strongest predictors of ball spin based on the third model, therefore the final model linked the human kinematics to the best predictor of spin from the racket. Model D acknowledges the influence of racket kinematics on ball spin, but aims to quantify what contributions the human kinematics play in attaining the desirable racket kinematics linked with high ball spin rates. Splitting the data into individual models in this way not only answers specific questions, but also ensured an appropriate sample size for the number of predictors entered into each regression model, based on the recommendation of 10-15 samples for each predictor (Field, 2009).

Exploratory regression analyses were run for each model to ascertain which variables contributed to the prediction of ball spin. The chosen variables were based on previous research and if a significant difference was observed between the flat and topspin strokes (Chapter 5). The variables based on previous research (Groppel *et al*., 1983; Knudson, 1991) were identified as the vertical velocity, trajectory and inclination of the racket. Overall racket velocity may also be important in order for the effects of the Magnus force to be maximised (Bartlett, 1997). As exploratory analyses, all variables were entered into the model simultaneously, therefore giving no indication of hierarchy or bias (Field, 2009).

The results of the exploratory analyses were used to produce final models that removed those variables not found to be reliable predictors. The influence of the predictors on the dependent variable in each model was based on the t-statistic with an alpha level set at 0.05. Tables 6.1 and 6.2 identify the initial variables entered into each model for the exploratory analysis and final analysis based on this statistic, for the forehand and backhand respectively.

Table 6.1 – Regression models and the predictors entered for the exploratory and final models for the forehand stroke.

Model	Exploratory Predictors	Final Predictors
A - Prediction of ball spin from racket kinematics	Vertical racket velocity Racket angle Racket inclination Racket velocity vector Racket Low-High	Vertical racket velocity Racket inclination
B - Prediction of ball spin from human kinematics	Vertical forearm velocity Racket motion w.r.t. forearm Forearm pronation velocity Elbow flexion velocity Vertical upper arm velocity Shoulder Abduction velocity Internal rotation of upper arm velocity Hip extension Hip extension velocity	Vertical forearm velocity Hip extension Internal rotation of upper arm velocity Forearm pronation velocity
C - Prediction of ball spin from racket and human kinematics	Vertical racket velocity Racket inclination Vertical forearm velocity Forearm pronation velocity Internal rotation of upper arm velocity Hip extension	Vertical racket velocity Racket inclination Hip extension Internal rotation of upper arm velocity
D - Prediction of vertical racket velocity from human kinematics	Vertical forearm velocity Racket motion w.r.t. forearm Forearm pronation velocity Elbow flexion velocity Vertical upper arm velocity Shoulder Abduction velocity Internal rotation of upper arm velocity Hip extension Hip extension velocity	Vertical forearm velocity Hip extension Forearm pronation velocity Internal rotation of upper arm velocity

Table 6.2 – Regression models and the predictors entered for the exploratory and final models for the backhand stroke.

Model	Exploratory Predictors	Final Predictors
A - Prediction of ball spin from racket kinematics	Vertical racket velocity Racket angle Racket inclination Racket velocity vector Racket Low-High	Vertical racket velocity Racket inclination Racket Low-High
B - Prediction of ball spin from human kinematics	Vertical forearm velocity Forearm supination Forearm supination velocity Elbow flexion Elbow flexion velocity Vertical upper arm velocity Hip extension Hip extension velocity	Vertical forearm velocity Vertical upper arm velocity Elbow flexion velocity Forearm supination velocity Hip extension Forearm supination
C - Prediction of ball spin from racket and human kinematics	Vertical racket velocity Racket inclination Racket Low-High Vertical forearm velocity Vertical upper arm velocity Elbow flexion velocity Forearm supination velocity Hip extension Forearm supination	Vertical racket velocity Racket inclination Racket Low-High
D - Prediction of vertical racket velocity from human kinematics	Vertical forearm velocity Forearm supination Forearm supination velocity Elbow flexion Elbow flexion velocity Vertical upper arm velocity Hip extension Hip extension velocity	Vertical forearm velocity Vertical upper arm velocity Elbow flexion velocity Hip extension Forearm supination velocity Forearm supination

The importance of each predictor variable was determined by the unstandardised and standardised beta statistics. The unstandardised statistic is the coefficient indicating the strength of the relationship between the predictor and dependent variables, when all other factors are held constant (Field, 2009). The statistic indicates the change in the dependent variable as a result of a one unit change in the mean of the predictor variable. The standardised statistic works in the same way, but in relation to the standard deviation of each variable. Therefore, the statistic provided indicates the number of standard deviations the dependent variable changes as a result of a one standard deviation change in the predictor variable, when all others are held constant (Field, 2009). The significance of these predictors was assessed using the t-statistic with an alpha level of 0.05.

The standardised beta statistic of influence on the dependent variable was used to determine the order of entry for the final model. For each final model, the variables were entered hierarchically based on this statistic, enabling the importance of each predictor to the dependent variable to be fully explained. This hierarchical order is reflected in the order by which the variables in the right-hand column of Tables 6.1 and 6.2 are presented.

At each stage of the analyses, the assumptions of multiple regression model were checked, and the influence of each specific sample on the model analysed. The distribution of residuals in the model was matched with a histogram with a normal curve, these were considered to be normally distributed if the mean of errors tended to zero, and the distribution approximated the normal curve. The percentage of standardised residuals outside the 2 and 2.5 standard deviations was used as a further measure to confirm this. Normality could be assumed if the percentages were less than 5 and 2.5, respectively (Field, 2009). The homoscedasticity of predictors was assessed by comparing the standardised predicted value with the standardised residual, and was assumed to be met if the distribution of scores appeared to be randomly dispersed around zero. The assumption of independent, or uncorrelated, errors was assessed by the Durbin-Watson statistic. Errors were assumed to be uncorrelated if this value was in the range 1-3 (Field, 2009). Finally, the collinearity of predictor variables was assessed using the VIF and tolerance statistics. The variables were assumed not to have significant collinearity if the largest VIF statistic was below 10, and the tolerance was above 0.2 according to the recommendations of Field (2009).

Casewise diagnostics were produced to assess if any particular sample held any undue influence over the model. Cook's distance, Mahalanobis distance, average leverage and Dfbeta statistics were produced to assess this potential influence. Cook's distance measures the influence of a single sample on the whole model's ability to predict the dependent variable. Samples less than 1 were considered not to have undue influence (Field, 2009). The Mahalanobis distance is the distance between each case and the mean of the predictor variables. Based on the number of predictor and sample size, values less than 15 were not considered to be of concern (Field, 2009). The average leverage statistic measures the influence of the outcome value over predicted values, a leverage of zero indicates the case has no influence over prediction of the outcome, whereas a value of one indicates complete influence over prediction. Values greater than three times the average leverage value were considered to have undue leverage (Field, 2009), this is calculated as shown;

$$\text{Average Leverage} = 3\,\frac{(x+1)}{n}$$

Where *x* is the number of predictors, and *n* is the number of samples.

The final diagnostic check was to analyse the standardised Dfbeta values. This statistic examines the effect removing a sample will have on the regression equation. Samples were considered to have a non-significant effect if the standardised statistic was less than one (Field, 2009).

The volume of casewise diagnostics indicates that there are a number of ways for a regression model to be validated, and a number of ways that a model might be compromised. Whilst each statistic has its own threshold criteria, the guidelines for using these statistics are less clear. The approach advocated by Tabachnick and Fidell (2007) is to remove samples where these statistics reveal that the precision of the model is compromised. This approach seems logical statistically, but not if a sample is an outlier due to natural variation and is therefore from real data. Field's (2009) summary suggests that diagnostics should not be utilised to justify removing samples to improve the regression parameters, merely to highlight their existence. The approach of the present study is to use these diagnostic statistics to comment on the regression models used, and by extension, their validity in extending the findings within them to a wider population. Where casewise diagnostics do reveal an undue influence of a sample on the model, those samples are retained in the results presented in this chapter. However, the statistical effect of removing these samples is explored by removing the samples and rerunning the models concerned. These results are attached in Appendix C3.1 and C3.2.

6.3 RESULTS

The assumptions of normally distributed errors, independent errors and homoscedasticity of predictor variables were met for each model for the forehand and backhand strokes, with one exception. The assumption of independent errors, measured by the Durbin-Watson test, was not met for model D in the forehand stroke. This suggests that some of the errors in this model are correlated. This limits some of the statistical significance of this particular model, but the results appear reliable in the context of the other models of the forehand. The VIF and tolerance statistics indicated that the collinearity of the predictor variables in all models was not significant.

For the forehand and backhand strokes the casewise diagnostics revealed no issues for Model A (prediction of ball spin from racket kinematics). However, the other models for both strokes contain some cases that may have unduly influenced the model. The results for these models without the influential cases are presented in Appendix C3.1 and C3.2. A comparison between the models with and without these cases revealed that the absence of the cases reduced the explained variance of the model, typically by 2 %, but did not significantly alter the model. In all instances, the same predictors remained significant, in the same order of importance with slight alterations to the coefficients. It is concluded that the models presented here are a good representation of the strongest predictors of ball spin rate, however some caution should be taken in applying the coefficients accompanying each variable.

6.3.1 FOREHAND

Group means and deviations for the combination of flat and topspin stroke are presented in Table 6.3. The means can be related to the unstandardised beta coefficients to understand the unit change in the dependent variable, whilst the standard deviations are related to the standardised beta coefficients to explain the variation in the dependent variable (Tables 6.4-6.7). The prediction of ball spin from racket kinematics (Table 6.4), human kinematics (Table 6.5) and all kinematics (Table 6.6), and the prediction of vertical racket velocity from human kinematics (Table 6.7) are presented in turn. The levels of each model (Tables 6.4-6.7) represent the addition of each variable, based on the hierarchy established from the exploratory analyses.

Table 6.3 – Mean and standard deviations of ball spin and the significant predictor variables for the forehand stroke.

	Mean	Standard Deviation
Ball Spin (rev.min^{-1})	1169.35	753.31
Vertical Racket Velocity (m.s^{-1})	7.08	3.29
Racket Inclination (°)	3.96	8.21
Vertical Forearm Velocity (m.s^{-1})	2.22	0.93
Hip Extension (°)	46.33	21.60
Upper Arm Internal Rotation Velocity (°.s^{-1})	207.42	293.44
Forearm Pronation Velocity (°.s^{-1})	397.83	277.40

Table 6.4 – Final model of prediction of ball spin from racket kinematics (Model A).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
A1	(Constant)	-45.69	88.70		0.56*
	Vertical Racket Velocity	171.70 *	11.37 *	0.75 *	
A2	(Constant)	44.52	85.65		0.61*
	Vertical Racket Velocity	146.00 *	11.97 *	0.64 *	
	Racket Inclination	23.16 *	4.79 *	0.25 *	

*Variable significantly contributes to the model ($p < 0.05$).

The vertical racket velocity was the strongest predictor of ball spin rate, accounting for 56% of the variation in spin (Table 6.4). The addition of the racket inclination increased the strength of prediction by 5%, but the vertical racket velocity remained the strongest predictor.

The vertical velocity of the forearm was the strongest predictor of ball spin rate, based on human kinematics (Table 6.5). This accounted for 26% of the variation in spin. Hip flexion, and the velocities of external rotation of the upper arm and forearm pronation also significantly ($P < 0.050$) contributed to the model, accounting for a further 11% in the variation in spin.

Table 6.5 – Final model of prediction of ball spin from human kinematics (Model B).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
B1	(Constant)	244.76	129.06		0.26*
	Vertical Forearm Velocity	413.32 *	53.59 *	0.51 *	
B2	(Constant)	-33.49	140.63		0.33*
	Vertical Forearm Velocity	335.12 *	54.64 *	0.41 *	
	Hip Extension	9.76 *	2.36 *	0.28 *	
B3	(Constant)	-206.82	164.06		0.35*
	Vertical Forearm Velocity	348.59 *	54.58 *	0.43 *	
	Hip Extension	11.28 *	2.46 *	0.32 *	
	Internal Upper Arm Rotation Velocity	0.35 *	0.18 *	0.14 *	
B4	(Constant)	-375.88	177.41		0.37*
	Vertical Forearm Velocity	327.33 *	54.65 *	0.40 *	
	Hip Extension	10.98 *	2.44 *	0.31 *	
	Internal Upper Arm Rotation Velocity	0.56 *	0.19 *	0.22 *	
	Forearm Pronation Velocity	0.47 *	0.20 *	0.17 *	

*Variable significantly contributes to the model ($p < 0.05$).

When the racket and human predictors of ball spin rate were considered together the racket predictors were strongest (Table 6.6), but hip flexion and the external rotation velocity of the upper arm also significantly ($p < 0.050$) contributed to the prediction.

The vertical velocity of the forearm was the strongest predictor of the vertical racket velocity (Table 6.7), accounting for 38% of the variation in that measure. However, hip flexion and the velocity of the upper limb rotations were also significant predictors ($p < 0.050$), accounting for a further 7% of the variation in vertical racket velocity.

Table 6.6 – Final model of prediction of ball spin from racket and human kinematics (Model C).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
C1	(Constant)	-46.06	89.77		0.56*
	Vertical Racket Velocity	171.21 *	11.49 *	0.75 *	
C2	(Constant)	49.23	86.82		0.61*
	Vertical Racket Velocity	144.96 *	12.11 *	0.63 *	
	Racket Inclination	23.39 *	4.85 *	0.26 *	
C3	(Constant)	-46.29	103.61		0.62
	Vertical Racket Velocity	139.20 *	12.53 *	0.61 *	
	Racket Inclination	21.42 *	4.97 *	0.23 *	
	Hip Extension	3.10	1.86	0.09	
C4	(Constant)	-171.43	116.49		0.63*
	Vertical Racket Velocity	139.12 *	12.39 *	0.61 *	
	Racket Inclination	22.19 *	4.93 *	0.24 *	
	Hip Extension	4.45 *	1.93 *	0.13 *	
	Internal Rotation of Upper Arm Velocity	0.29 *	0.13 *	0.11 *	

*Variable significantly contributes to the model ($p < 0.05$).

Table 6.7 – Final model of prediction of vertical racket velocity from human kinematics (Model D).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
D1	(Constant)	2.18	0.52		0.38*
	Vertical forearm velocity	2.20 *	0.21 *	0.62 *	
D2	(Constant)	1.26	0.57		0.42*
	Vertical forearm velocity	1.94 *	0.22 *	0.54 *	
	Hip Extension	0.03 *	0.01 *	0.21	
D3	(Constant)	1.04	0.57		0.44*
	Vertical forearm velocity	1.84 *	0.22 *	0.52 *	
	Hip Extension	0.03 *	0.01 *	0.18 *	
	Forearm Pronation Velocity	> 0.01 *	> 0.01 *	0.13 *	
D4	(Constant)	0.16	0.72		0.45*
	Vertical forearm velocity	1.85 *	0.22 *	0.52 *	
	Hip Extension	0.03 *	0.01 *	0.22 *	
	Forearm Pronation Velocity	> 0.01 *	> 0.01 *	0.20 *	
	Internal Rotation Upper Arm Velocity	> 0.01 *	> 0.01 *	0.14 *	

*Variable significantly contributes to the model ($p < 0.05$).

6.3.2 BACKHAND

Group means and deviations for the combination of flat and topspin strokes are presented in Table 6.8. The means can be related to the Unstandardised beta coefficients to understand the unit change in the dependent variable, whilst the standard deviations are related to the standardised beta coefficients to explain the variation in the dependent variable (Tables 6.9-6.11). The prediction of ball spin from racket kinematics (Table 6.9), human kinematics (Table 6.10), and the prediction of vertical racket velocity from human kinematics (Table 6.11) are presented in turn. The exploratory analysis revealed that the predictor variables of ball spin when all kinematics were entered were identical to the racket analysis. Therefore, the results are the same as those presented in Table 6.9. The levels of each model (Tables 6.9-6.11) represent the addition of each variable, based on the hierarchy established from the exploratory analyses.

Table 6.8 – Mean and standard deviations of ball spin and the significant predictor variables for the backhand stroke.

	Mean	Standard Deviation
Ball Spin (rev.min^{-1})	826.42	689.86
Vertical Racket Velocity (m.s^{-1})	5.47	3.01
Racket Inclination (°)	3.97	7.06
Racket Low-High (m)	0.19	0.15
Vertical Forearm Velocity (m.s^{-1})	1.78	1.02
Vertical Upper arm Velocity (m.s^{-1})	0.93	0.60
Hip Extension (°)	25.78	16.00
Elbow Flexion Velocity (°.s^{-1})	125.44	323.87
Forearm Supination (°)	9.70	19.96
Forearm Supination Velocity (°.s^{-1})	373.74	316.66

Table 6.9 – Final model of prediction of ball spin from racket kinematics (Model A).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
A1	(Constant)	-196.36	61.52		0.67*
	Vertical Racket Velocity	186.84 *	9.85 *	0.82 *	
A2	(Constant)	-108.24	60.56		0.71*
	Vertical Racket Velocity	153.12 *	11.51 *	0.67 *	
	Racket Inclination	24.27 *	4.91 *	0.25 *	
A3	(Constant)	-99.82	59.46		0.72*
	Vertical Racket Velocity	176.84 *	13.99 *	0.77 *	
	Racket Inclination	20.81 *	4.96 *	0.21 *	
	Racket Low-High	-650.01 *	226.80 *	-0.14 *	

*Variable significantly contributes to the model ($p < 0.05$).

The vertical racket velocity was the strongest predictor of the ball spin rate (Table 6.9), accounting for 67% in the variation in spin. However, the racket inclination and the low-to-high trajectory of the racket were also significant predictors ($p < 0.05$).

The vertical velocity of the forearm was the strongest predictor of the ball spin rate when human kinematics were considered alone (Table 6.10). However, this only accounted for 4% of the variation in spin rate, and this was significantly ($p < 0.05$) improved by each of the other predictors, accounting for an additional 43% of the variation in spin.

A similar pattern was also observed for the prediction of vertical racket velocity from human kinematics (Table 6.11). However, a total of 65% of the variation in this measure was accounted for by the completed model.

Table 6.10 – Final model of prediction of ball spin from human kinematics (Model B).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
B1	(Constant)	583.48	100.33		0.04*
	Vertical Forearm Velocity	129.74 *	49.03 *	0.20 *	
B2	(Constant)	598.03	94.93		0.15*
	Vertical Forearm Velocity	521.18 *	95.44 *	0.78 *	
	Vertical upper arm velocity	-762.08 *	162.41 *	-0.67 *	
B3	(Constant)	104.67	112.08		0.33*
	Vertical Forearm Velocity	675.78 *	88.36 *	1.01 *	
	Vertical upper arm velocity	-673.27 *	145.80 *	-0.59 *	
	Elbow Flexion Velocity	1.08 *	0.16 *	0.52 *	
B4	(Constant)	7.41	117.25		0.35*
	Vertical Forearm Velocity	599.55 *	92.37 *	0.90 *	
	Vertical upper arm velocity	-564.04 *	150.33 *	-0.50 *	
	Elbow Flexion Velocity	1.09 *	0.16 *	0.52 *	
	Forearm Supination Velocity	0.35 *	0.14 *	0.16 *	
B5	(Constant)	-233.29	128.82		0.40*
	Vertical Forearm Velocity	597.18 *	88.89 *	0.90 *	
	Vertical upper arm velocity	-622.05 *	145.43 *	-0.55 *	
	Elbow Flexion Velocity	1.06 *	0.15 *	0.51 *	
	Forearm Supination Velocity	0.46 *	0.14 *	0.21 *	
	Hip Extension	10.13 *	2.62 *	0.24 *	
B6	(Constant)	-208.21	122.10		0.47*
	Vertical Forearm Velocity	579.23 *	84.25 *	0.87 *	
	Vertical upper arm velocity	-624.33 *	137.70 *	-0.55 *	
	Elbow Flexion Velocity	0.81 *	0.16 *	0.38 *	
	Forearm Supination Velocity	0.63 *	0.14 *	0.29 *	
	Hip Extension	13.05 *	2.56 *	0.31 *	
	Forearm Supination	-10.10 *	2.20 *	-0.30 *	

*Variable significantly contributes to the model ($p < 0.05$).

Table 6.11 – Final model of prediction of vertical racket velocity from human kinematics (Model D).

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient	R^2
D1	(Constant)	4.39	0.44		0.04*
	Vertical Forearm Velocity	0.58 *	0.22 *	0.20 *	
D2	(Constant)	4.47	0.40		0.20*
	Vertical Forearm Velocity	2.68 *	0.40 *	0.92 *	
	Vertical upper arm velocity	-4.10 *	0.69 *	-0.82 *	
D3	(Constant)	1.68	0.43		0.49*
	Vertical Forearm Velocity	3.56 *	0.34 *	1.22 *	
	Vertical upper arm velocity	-3.59 *	0.55 *	-0.72 *	
	Elbow Flexion Velocity	0.01 *	< 0.01 *	0.67 *	
D4	(Constant)	0.39	0.42		0.60*
	Vertical Forearm Velocity	3.69 *	0.30 *	1.26 *	
	Vertical upper arm velocity	-4.16 *	0.50 *	-0.84 *	
	Elbow Flexion Velocity	0.01 *	< 0.01 *	0.65 *	
	Hip Extension	0.06 *	0.01 *	0.33 *	
D5	(Constant)	-0.19	0.45		0.62*
	Vertical Forearm Velocity	3.36 *	0.31 *	1.15 *	
	Vertical upper arm velocity	-3.72 *	0.50 *	-0.75 *	
	Elbow Flexion Velocity	0.01 *	< 0.01 *	0.65 *	
	Hip Extension	0.07 *	0.01 *	0.37 *	
	Forearm Supination Velocity	< 0.01 *	< 0.01 *	0.17 *	
D6	(Constant)	-0.11	0.43		0.65*
	Vertical Forearm Velocity	3.30 *	0.30 *	1.13 *	
	Vertical upper arm velocity	-3.73 *	0.48 *	-0.75 *	
	Elbow Flexion Velocity	0.01 *	< 0.01 *	0.57 *	
	Hip Extension	0.08 *	0.01 *	0.42 *	
	Forearm Supination Velocity	< 0.01 *	< 0.01 *	0.22 *	
	Forearm Supination	-0.03 *	0.01 *	-0.20 *	

*Variable significantly contributes to the model ($p < 0.05$).

6.4 DISCUSSION

The aim of the analyses presented here was to establish which kinematic variables are the best predictors of high ball spin rates indicative of topspin. The combination of four regression models of the forehand and backhand groundstrokes has revealed the best predictors of ball spin based on racket kinematics, and the human kinematic variables that produce the associated racket kinematics.

In order to place the results of this analysis into some context, it is important to acknowledge the limitations of multiple regression modelling of a linked system such as the human body. One of the key assumptions of regression is that the predictor variables are independent of each other, and that they have a limited amount of shared variance. From a statistical perspective, this assumption was met for each model produced based on the methods presented in this chapter. However, realistically this assumption can not be met for the human body because it is a kinetic chain of linked body segments that do not always move independently. For example, there would be almost identical variation in the vertical velocity of the forearm and upper arm body segments if there was no angular change at the elbow. Therefore, the exploratory analyses removed some variables from the models that might logically have been good predictors of ball spin. Perhaps the clearest example of this is the kinematics of the racket. High upward racket velocities and an upward racket trajectory at ball impact have both been linked to the production of topspin in the forehand (Knudson, 1991). However, the racket angle to the horizontal at impact in the present study was calculated using the instantaneous upward and horizontal velocities. This meant that these two measures accounted for much of the same variation in the ball spin rate, and as the strongest predictor of the two, only the upward velocity of the racket was retained in the model despite both variables strongly correlating with ball spin.

The analysis presented here has identified the most reliable and strong predictors of ball spin and has investigated the factors that link with this more proximally in the kinematic chain. However, the reader should be aware that other kinematic variables may also predict ball spin rates and may also be important factors.

6.4.1 FOREHAND

The vertical velocity of the racket at impact was identified as the strongest predictor of ball spin, accounting for more variation in spin rate than any other variable. In turn, the upward movement of the upper limb was found to be the primary driver of this movement, along with some contribution from hip extension. The following discussion will examine the predictors preeminent in each model.

The vertical velocity and inclination of the racket were the best predictors of ball spin rate, accounting for 61% of the variation. When both of these variables are considered together, an increase of 1 $m.s^{-1}$ vertical velocity leads to an increase of 146 $rev.min^{-1}$, and an increase in racket inclination of 1° leads to an increase of 23 $rev.min^{-1}$ (Table 6.4), if the other variable is held constant. In addition to these variables, the trajectory of the racket in the forward swing has also been identified as a key factor for producing topspin (Knudson, 1991). Neither the racket angle to the horizontal nor the increase in racket height prior to impact were significant predictors of ball spin when the vertical velocity and inclination were considered. It is likely that these variables would contribute to some of the 39% of variation missing from this model.

The human kinematics accounted for just 37% of the variation in ball spin. The main contribution to this was the vertical velocity of the forearm, a 1 $m.s^{-1}$ increase in this measure equated to a 327.33 $rev.min^{-1}$ increase in ball spin rate when all other factors were held constant. The next largest contributor was the extension of the hip, whereby a 21.6° increase in extension equated to an increase of 233.53 $rev.min^{-1}$. A $1°.s^{-1}$ increase in the angular velocities of the internal rotation of the upper arm and pronation of the forearm also contributed by increasing ball spin rates by 0.56 $rev.min^{-1}$ and 0.47 $rev.min^{-1}$ respectively. This may not seem a great amount, but based on an increase of one standard deviation in each of these measures ball spin rate would increase by 165.73 $rev.min^{-1}$ as a result of internal rotation of the upper arm, and by 128.06 $rev.min^{-1}$ as a result of forearm pronation (Table 6.5). It is interesting that the pronatory action of the forearm is related to the spin rate of the ball, as the significance of this action had been previously discounted (Knudson, 1991). However, the overall contribution of the variables to ball spin rate is not large, so the individual coefficients should be interpreted with caution.

It is tempting to conclude that the racket is responsible for 61 % of the variation in ball spin rate, and human kinematics are responsible for 37 %, therefore most of the factors that influence spin rate are accounted for. However, when all predictors of ball spin rate are considered, the main contributors are the racket parameters, with the human kinematics adding just 2% to the model (Table 6.6). The main predictor of ball spin rate from human kinematics was the vertical velocity of the forearm, but this was not retained in the model, probably due to its high shared variance with the vertical velocity of the racket. This does not mean that the upward velocity of the forearm is not an important factor, merely that the upward velocity of the racket is a better predictor. This is most likely due to the proximity of the racket to the ball in comparison to the forearm.

Thus far, the regression models have indicated that racket kinematics are the primary predictors of the ball spin rate. However, players, coaches and biomechanists are interested not only in the end result, but also which actions drive these racket kinematics. As upward racket velocity is the strongest predictor of ball spin rate, it is interesting to note which variables are linked with this action. The human variables entered into the model predicted 45% of the variation in the upward velocity of the racket. The upward velocity of the forearm was the strongest predictor of this action, with a 1 $m.s^{-1}$ increase in forearm velocity equating to a 1.85 $m.s^{-1}$ increase at the racket, when all other factors are held constant. Hip extension served to increase the upward velocity of the racket, with 21.6° (1 SD) of extension equating to 0.72 $m.s^{-1}$ of upward velocity. There were also smaller contributions from the angular velocities of the upper arm and forearm about their long axes. Internal rotation of the upper arm and forearm pronation may not seem the most instantly logical drivers of upward racket movement. However, the more modern tennis techniques utilise these types of rotation to generate racket velocity (Marshall and Elliott, 2000), and may also use them to raise the racket from a low to a high position during the forward swing.

The combination of the four regression models has revealed that the upward velocity of the racket, and the racket inclination at impact, are the strongest predictors of ball spin rate. The addition of human kinematics to these factors only improves the strength of this prediction by accounting for a further 2% of the variation. Thus, 37 % of the variation in ball spin rate remains unexplained. Groppel *et al*. (1983)

identified factors such as the inbound spin rate, velocity of the ball and the impact characteristics to be important. However, the present study attempted to control for these factors through the use of a reliable ball machine and the use of two rackets strung to a similar tension with the same material. The error in these measurements (Chapter 4.2) is likely to account for some, but not all, of this unexplained variance. Groppel *et al*. (1983) contended that the location of ball impact on the racket explained some of the error in their predictive model of spin, as it was based only on central impacts. Brody (2002) suggests that an off-centre impact location on the strings is preferable for playing a topspin stroke as it allows the ball to roll and bite over a larger area before leaving the racket, and is therefore less likely to contact near, or onto the frame. The precise optimal point is dependent on the angle of incidence between the incoming ball and the trajectory of the racket. Cross (2002a) explains that the relative angles and velocities of the ball and racket to the court surface determines the angle of incidence. If the respective angles and velocities of the racket and ball are equal, then the ball will contact the strings of the racket at a right angle. In this case the friction between the strings and ball will reduce the spin rate. Cross (2002a) states that the optimal angle of incidence for maximising topspin is 40°, and that this is easier to achieve when the ball is falling as it increases the relative velocity of the racket and ball. Despite the attempt of the present study to control the initial conditions of the ball for each participant and within each testing session, the variables stated above may account for some of the unexplained variance in the spin of the ball.

The unexplained variation in vertical racket velocity, as predicted by the human kinematic variables, is more difficult to explain. Only four of the nine predictors entered into the exploratory model were retained for the final analysis. Each of the five omitted variables were logically expected to contribute to the upward movement of the racket, but seemed to contribute much of the same variance identified by the previous four. The reason for the amount of unexplained variance for this model is difficult to explain, but may be due to a statistical anomaly due to the relative strengths of the correlations and is perhaps indicative of the low score of the Durbin-Watson test. Therefore, this particular model will provide no more than a moderate prediction of the vertical velocity of the racket. It should be noted that, whilst not significant predictors, the variables omitted may still be important in spin production. In this regard, consideration must also be given for the analysis of the previous chapter.

6.4.2 BACKHAND

The upward vertical velocity of the racket was the strongest predictor of the ball spin rate in the backhand stroke, with the upward velocity of the forearm being the strongest predictor of the upward velocity of the racket. However, in contrast to the forehand, the relationship between these factors appears to be more complicated, with more variables involved. This complexity may be a result of the participants using a mixture of single- and double-handed grips. Whilst the two types of backhand strokes have different kinematic patterns, the relationship between the rate of ball spin and the strongest kinematic predictors remains similar regardless of grip type. Therefore, the results presented here relate to the strongest predictors of ball spin rate from all types of backhand observed in the present study. The predictors for the single- and double-handed backhands are appended for further interest (Appendix C3.3).

The kinematics of the racket accounted for 72% of the variation in the spin rate of the ball. The majority of this was due to the upward velocity of the racket, with a 1 $m.s^{-1}$ increase in this velocity equating to an increase spin of 176 $rev.min^{-1}$. Smaller effects were also observed for the inclination and trajectory of the racket. Positioning the racket-head to a orientation tilted forward by 1° was found to increase spin by 20 $rev.min^{-1}$, whilst an upward racket trajectory towards impact of around 0.15 m, was found to alter the spin rate by approximately 97 $rev.min^{-1}$ (Table 6.9). The importance of these predictors to the ball spin rate is in agreement with Groppel *et al*. (1983). However, the increase in racket trajectory was found to reduce ball spin when other variables were held constant, despite a positive correlation between these variables. It should not be interpreted that an upward trajectory is detrimental to producing topspin, merely that this variable makes a negative contribution to the model when the vertical velocity and inclination of the racket are used as predictors (Tabachnick and Fidell, 2007).

The final analysis of the prediction of ball spin rate based on human kinematics revealed 6 predictors that made a significant contribution accounting for 47 % of the variation in the spin of the ball. The vertical velocity of the upper arm and forearm were the strongest predictors of ball spin, with the ball spin deviating by 624 and 579 rev.min^{-1} respectively with a 1 m.s^{-1} change in these measures. However, the predictive power of the forearm velocity only increased when the upper arm was considered (Note the change from model 2.1 to 2.2 – Table 6.10), therefore both of these measures should be used to make a reliable prediction based on human kinematics. The next strongest predictor was the flexion velocity at the elbow, with a 324°.s^{-1} (1 SD) increase positively affecting ball spin by 262 rev.min^{-1}. The importance of elbow flexion in the double-handed backhand stroke means that this is a more significant measure for players using the double-handed grip, and does not mean that players with a single-handed grip should seek to alter stroke mechanics. Appendix C3.3 provides separate regression models for the single- and double-handed backhand strokes. Hip extension, forearm supination and supinatory velocity all contributed by a similar amount with an increase of one standard deviation in each of these measures affecting the spin rate by 207 rev.min^{-1}. Interestingly, the supinatory velocity positively affected the model, whereas supination negatively affected the model. Again, it should not be interpreted that supination itself is not desirable, it is just the contribution it makes to the predictive equation of spin when all other variables are present.

When the significant predictors of ball spin rate based on racket and human kinematics were combined, only the racket kinematics were found to explain a significant portion of unique variance of the spin. Statistically, this is likely to be due to the small contributions that each human variable makes to the model. However, it should be noted that this does not mean that these measures are not important factors in driving the movement of the racket.

The combination of human kinematic variables accounted for 65 % of the variation in the upward velocity of the racket, which is itself the strongest predictor of ball spin rate. The strongest predictors of this are the upward velocity of the forearm and upper arm. The flexion of the forearm at the elbow, forearm supination and supinatory velocity and extension of the hip are also significant variables. The pattern and nature of these variables is identical to their prediction of ball spin rate, albeit with different values for the coefficients, underlining the link between the upward velocity of the racket and ball spin rate.

Analysis based on all models produced reveals that the racket kinematic variables are the strongest predictors of the ball spin rate, accounting for 72 % of the variation of the spin. The variables that may account for the remaining 28 % of variation are likely to be similar to those identified for the forehand. Interestingly, although the human kinematics could only predict 47 % of the variation in the ball spin rate, the same variables predicted 65 % of the upward velocity of the racket. This highlights the importance of extending the analysis past the racket, and investigating which kinematic factors are responsible for achieving desirable racket kinematics.

6.5 SUMMARY

The variables entered into the various models seeking to predict ball spin rate successfully produced reliable predictions of spin for the forehand and backhand strokes (Table 6.12). Though the predictive power of each of these models does vary, what this analysis has identified are key variables associated with producing topspin. This has extended the analysis of chapter 5 where differences between flat and topspin strokes were identified. Thus, the combined analysis of these two chapters has established the differences between flat and topspin strokes, and examined which of these differences is important in the context of producing topspin from the tennis groundstrokes.

What has also been established in these analyses thus far is that, despite the experimental controls implemented in the present study, tennis groundstrokes are highly variable. Much of this variation is related to different stroke technique. The analysis of the forehand revealed two distinct movement patterns (Chapter 5.4.1) whilst the single- and double-handed backhand grips yielded different kinematics, particularly in the flexion and extension of the arm at the elbow (Chapter 5.4.2) Therefore, the predictors identified in this chapter are representative of all of these variations, so it is important to establish to what extent the findings of the previous chapters hold true for individual players. Chapter 7 analyses individual case studies of performance to examine the kinematics of players producing higher ball spin rates in this context.

Table 6.12 – Kinematic variables related to ball spin and vertical racket velocity.

	Forehand	**Backhand**
Vertical Racket Velocity	✓	✓
Racket Inclination	✓	✓
Racket Trajectory (low-to-high)	✗	✓
Vertical Forearm Velocity	✓	✓
Vertical Upper Arm Velocity	✗	✓
Elbow Flexion-Extension Velocity	✗	✓
Forearm Pronation-Supination Velocity	✓	✓
Forearm Pronation-Supination	✗	✓
Internal Rotation of Upper Arm	✓	✗
Hip Flexion-Extension	✓	✓

Please note that the table merely summarises the important variables, and does not state which direction is important. For example, forearm pronation-supination velocity is a significant predictor for forehand and backhand strokes, but to increase topspin in the forehand, players should increase pronatory velocity whereas supination velocity positively relates to topspin in the backhand.

7. CASE STUDIES OF PLAYERS PRODUCING HIGH LEVELS OF BALL SPIN

7.1 INTRODUCTION

The preceding chapters identified kinematic differences between the flat and topspin strokes and established which variables best predicted ball spin. These results were established based on a cohort of tennis players, each with their own technique. The statistical analysis techniques have sufficient strength that these results can be generalised to a wider population. However, it may be informative to tennis professionals and their coaches to see if the results obtained are true of individual players. The intention of this chapter is to present individual case studies of the players producing a high amount of topspin for the forehand and backhand strokes. These case studies will be used to examine the extent that the previous analyses can be generalised to individuals within the cohort of participants in this investigation. This will highlight how useful the results of the preceding chapters are to coaches and players interested in increasing topspin production in their groundstrokes. Furthermore, this analysis will provide graphical information that will illustrate techniques that are successful in producing large amounts of topspin, thus overcoming the limitation of a variable cohort of players that was present in the previous analyses (Chapters 5 and 6).

7.2 FOREHAND – PARTICIPANT 18

Participant 18 presents an interesting case study for analysing the topspin forehand stroke as they were able to produce greater than 2000 $rev.min^{-1}$ for four out of the five experimental trials. The variables identified as strong predictors (Chapter 6), or strongly relating to ball spin rate resulting from a topspin forehand are presented for this participant alongside the group mean (Table 7.1).

Table 7.1 – Selected raw data for the topspin forehand of participant 18 and the group mean of all participants.

Trial	Ball Spin rate (rev.min^{-1})	Vertical Racket Velocity (m.s^{-1})	Upward Racket Displacement (m)	Racket Angle (°)	Racket Inclination (°)	Vertical Forearm Velocity (m.s^{-1})	Vertical Upper Arm Velocity (m.s^{-1})	Elbow Flexion Velocity (°.s^{-1})	Forearm Pronation Velocity (°.s^{-1})	Internal rotation velocity of upper arm (°.s^{-1})	Hip Extension (°)
1	2600.00	11.11	0.19	32.57	16.03	4.13	1.98	-187.71	-103.70	294.83	68.89
2	3533.33	10.98	0.17	27.11	15.82	3.47	1.80	33.53	317.84	216.09	50.81
3	2241.67	11.03	0.21	34.04	15.07	3.21	1.80	119.34	606.60	24.23	81.09
4	2820.83	12.84	0.25	36.58	15.12	3.53	1.90	-13.61	238.28	173.63	64.63
5	1445.83	10.82	0.22	32.40	5.54	3.89	1.83	-110.46	-408.40	165.45	61.98
Group Mean	1518.66	8.71	0.21	30.76	6.30	2.61	1.34	106.09	413.76	208.08	50.45

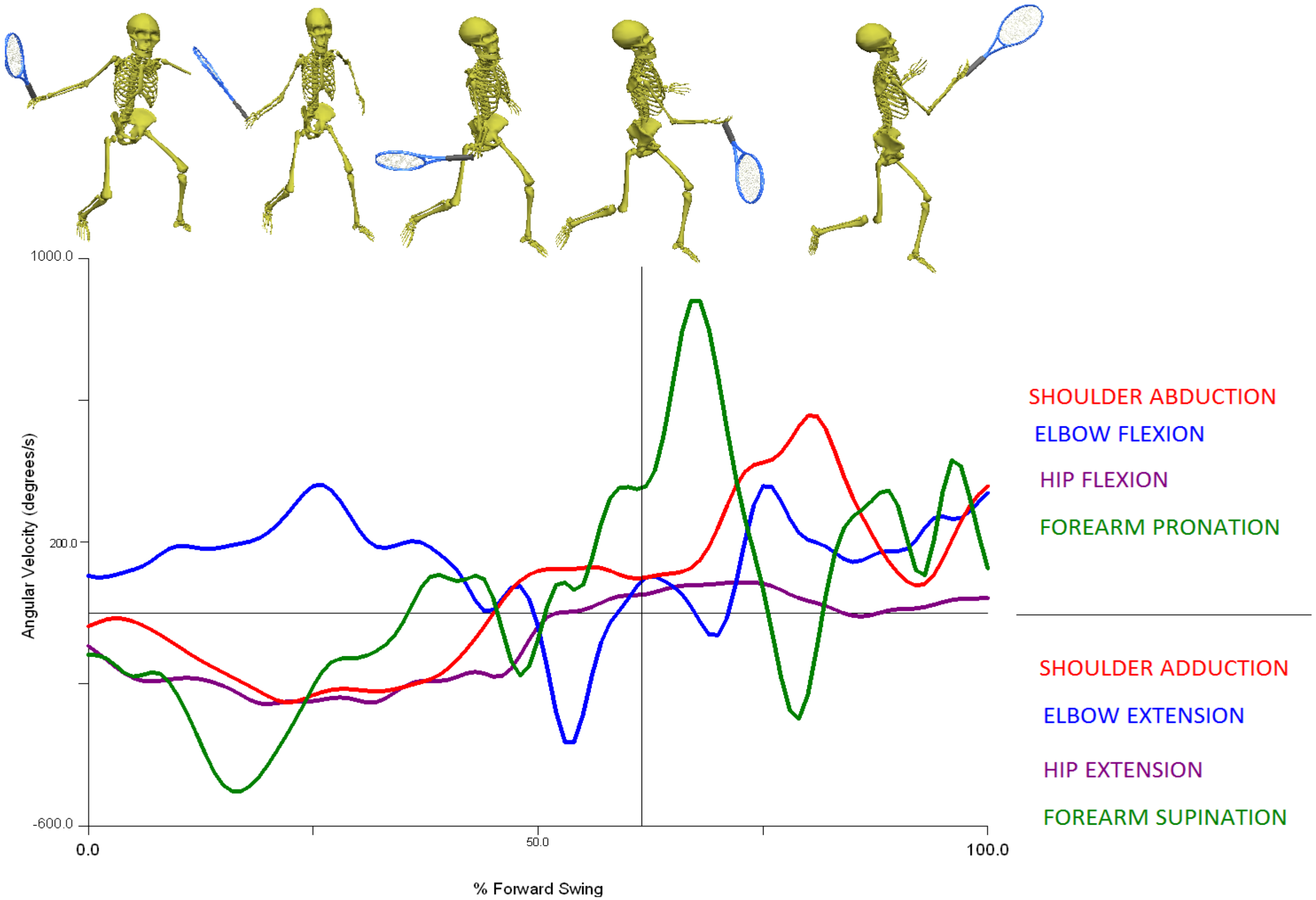


Figure 7.1 - Selected angular velocities in the forward swing during a topspin forehand. Shoulder abduction-adduction is calculated from the position of the upper arm relative to the trunk. Forearm pronation-supination is relative to the upper arm.

The racket kinematics of participant 18 are in keeping with the trends identified in Chapter 6 (6.4.1). The key predictors of high ball spin rates were the upward velocity and closed inclination of the racket at ball impact. Both of these measures were above that of the group mean for all trials, with the exception of trial 5 where the reduced inclination of the racket to the vertical corresponded with a reduced ball spin rate (Table 7.1). Interestingly, the racket inclination achieved by participant 18 was greater than that advocated by Knudson (1991), though it should be noted that this may be simply the ideal inclination for this player. For all participants, the upward trajectory and angle of the racket to the horizontal were significantly greater for topspin stroke (Chapter 5), but not found to be significant predictors of ball spin (Chapter 6). The results of participant 18 reflect the group means for these measures. Therefore, an upward trajectory of the racket may be important to produce topspin, but the magnitude of this upward movement seems less so.

The upper limb kinematics during the forward swing are characterised by an initial adduction of the upper arm at the shoulder to orient the arm alongside the trunk, followed by internal rotation of the upper arm to bring the racket forward. The arm then begins to abduct at the shoulder later in the forward swing. At this stage the forearm rotations of flexion at the elbow and pronation appear to be responsible for driving the racket upwards and achieving the correct racket-head position (Figure 7.1). These rotations are similar to those classified by Elliott *et al*. (1989a) as part of the multi-segment technique (Technique A – Figure 5.4). In comparison with the group mean in the present study, the upward velocities of the forearm and upper arm segments were larger for participant 18. The upward velocity of the forearm was a strong predictor of the upward velocity of the racket, whilst the same movement of the upper arm also correlates strongly with this action. However, the other predictors of upward racket velocity from the upper extremity do not differ from the group mean. Therefore, the increased velocity of the upper limb may be driven initially by hip extension, but later in the swing by abduction and elevation of the arm at the shoulder.

The main predictors of ball spin identified in the previous chapter (Chapter 6.4.1) appear responsible for the increased ball spin rate achieved for the topspin stroke by participant 18, in comparison to the group as a whole. However, these predictors do not appear to account for the variation in spin rate between the trials (Table 7.1). The reason for the reduced spin rate in trial 5 may be explained by the reduction in racket inclination, since all other key predictor variables remain of a similar magnitude as trials 1-4. This could underline the importance of each of these key elements being in place in order to achieve high ball spin rates. However, this does not account for the variation between trials 1-4. Applying the equation derived from the regression model of ball spin as predicted by racket kinematics, predicts that each of these trials will produce spin greater than 2000 rev.min^{-1}, but falls short of predicting the total spin rate in each case. It seems likely that variables such as impact location on the strings and the height of the ball will account for some of this discrepancy.

Despite the unexplained variation in ball spin rate between the experimental trials, this analysis has highlighted the importance of the variables identified in the previous chapter for producing topspin. This analysis should provide coaches and players with a concept of the extent of the magnitude required for each of these variables to achieve high topspin rates. Furthermore, the angular velocity pattern provided in Figure 7.1 illustrates a potential method of playing the stroke, though it should be noted that other methods may also produce large amounts of topspin.

7.3 BACKHAND

The preceding chapters have investigated the backhand groundstroke in the context of a single stroke type. This approach was justified as the strongest predictors of ball spin rate are the same for the single-handed and double-handed strokes. However, in the context of this analysis it is more appropriate to consider the different ways that each stroke type can produce topspin. Whilst the mean ball spin rate is greater for the participants playing with the double-handed grip (Tables 7.2 and 7.3), it is not the intention of this analysis to single out either approach as optimal for producing topspin. Indeed, the two participants presented here produced a near identical mean ball spin rate over five trials with contrasting grips. Therefore, the following examples illustrate how high topspin rates can be achieved with either type of grip.

7.3.1 – PARTICIPANT 5

Participant 5 was able to produce over 2000 rev.min^{-1} in four out of the five topspin trials recorded, playing a single-handed backhand. This was comfortably above the mean ball spin rate achieved with this backhand grip, and therefore provides an interesting case study. Table 7.2 presents the key predictors of ball spin rates resulting from backhand kinematics Illustration of the accompanying technique is also presented (Figure 7.2).

The upward velocity and inclination of the racket for the topspin trials of participant 5 were greater than all other players with a single-handed backhand in the present study. Both these variables were shown to be strong predictors of ball spin rate in the previous chapter (6.3.2). The upward velocities are more than double that of the group mean, whilst the inclination is four or five times greater than that of the mean. The upward trajectory is similar to the group as a whole, but the racket angles for the five trials of participant 5 indicate that this upward movement was executed much later in the forward swing. The racket angles at impact are indicative of a late upward trajectory (Figure 5.3), which reflects the recommendations of Knudson (1991) for producing topspin.

Table 7.2 – Selected raw data for the single-handed topspin backhand of participant 5 and the group mean of all participants with a single-handed stroke.

Trial	Ball Spin rate ($rev.min^{-1}$)	Vertical Racket Velocity ($m.s^{-1}$)	Upward Racket Displacement (m)	Racket Angle (°)	Racket Inclination (°)	Vertical Forearm Velocity ($m.s^{-1}$)	Vertical Upper Arm Velocity ($m.s^{-1}$)	Elbow Extension Velocity($°.s^{-1}$)	Forearm Supination Velocity ($°.s^{-1}$)	External rotation velocity of upper arm ($°.s^{-1}$)	Hip Extension (°)
1	2141.67	9.36	0.14	28.69	17.29	3.10	1.29	-175.48	1201.39	341.48	1.84
2	2533.33	10.14	0.15	26.16	12.07	3.79	1.68	24.24	1431.08	265.41	7.84
3	1941.67	11.66	0.24	37.43	13.13	3.79	1.75	9.45	934.63	372.37	28.30
4	2233.33	10.15	0.17	29.08	9.62	3.30	1.39	120.14	1169.80	379.40	11.93
5	2429.17	11.03	0.20	32.49	10.52	4.29	2.18	193.09	1261.52	377.98	23.56
Group Mean	940.44	5.89	0.20	17.72	2.55	2.81	1.43	151.72	616.22	243.54	28.13

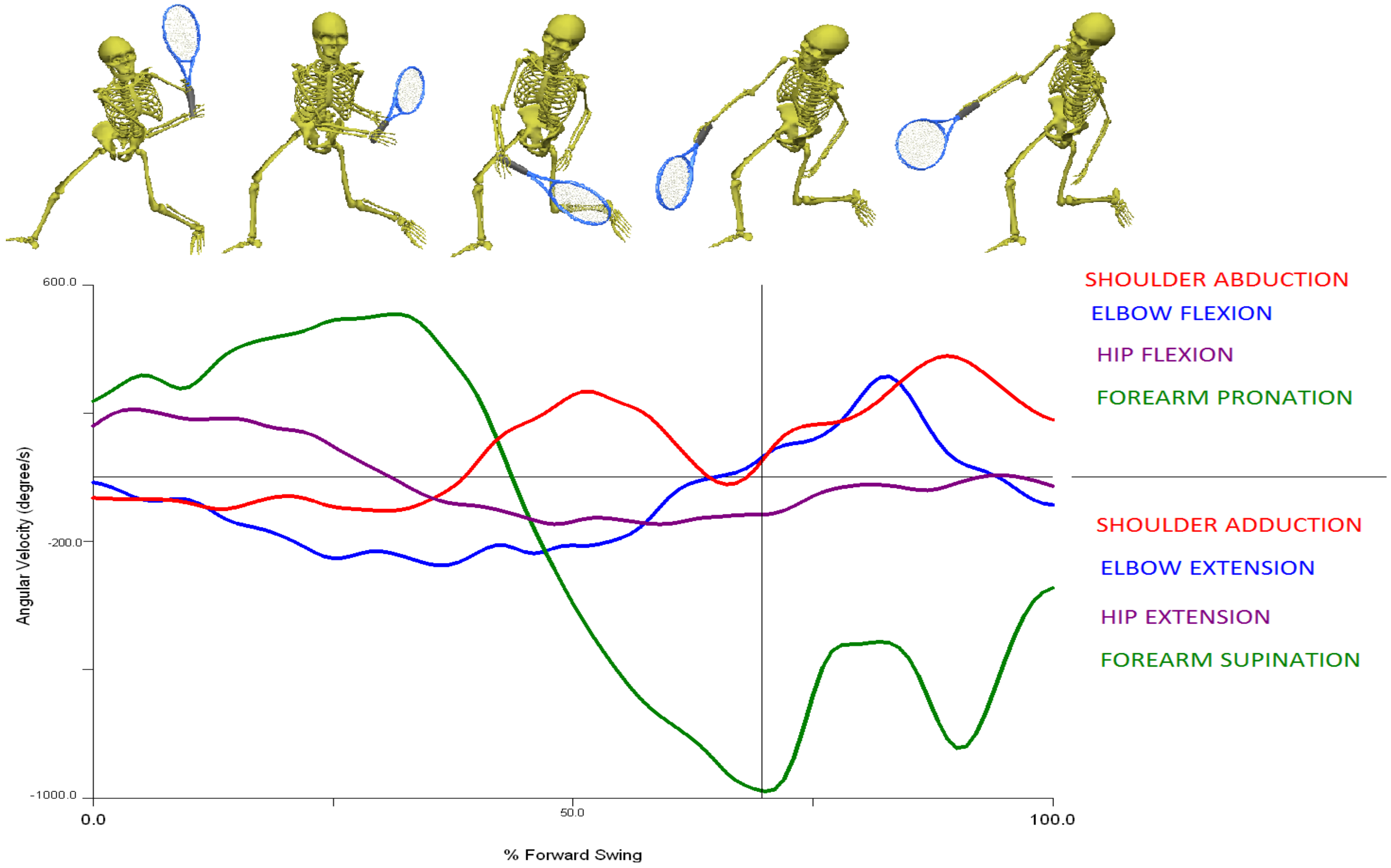


Figure 7.2 – Selected angular velocities in the forward swing during a single-handed backhand. Shoulder abduction-adduction is calculated from the position of the upper arm relative to the trunk. Forearm pronation-supination is relative to the upper arm.

The upward velocity of the upper limb, particularly the forearm, was above that of the group mean. These upward velocities are the strongest predictors of the upward velocity of the racket, and ball spin when racket kinematics are not considered. The kinematic pattern by which participant 5 is able to increase the velocity of the upper arm at impact is loosely based on a proximal-to-distal sequence, but is complicated by the rotations about the long axis of the upper limb. The principle of a summation of segment velocity along the kinetic chain has been shown previously to be complicated by these rotations (Marshall and Elliott, 2000). The initial driver of the upward movement of the player is through extension of the lower limb at the hip, whilst the arm begins to extend at the elbow to lower the racket (Figure 7.2). Once the rate of hip extension decelerates, the external rotation of the upper arm, along with trunk rotation, brings the racket forward. However, it appears to be the abduction of the shoulder that is responsible for the upward movement of the arm at this stage. The forearm also begins to rapidly supinate as the arm is moved forwards and upwards, and this movement continues until ball impact. This rapid supination serves to achieve the closed racket-head position at impact, but may also aid in the raising of the racket with respect to the upper limb towards ball impact.

This case analysis has demonstrated that high upward racket velocities and a closed racket-head at the point of ball impact are positively related to achieving high ball spin rates. It has also demonstrated that high upward velocities of the racket are achieved through high upward velocities of the arm. The control of the racket inclination at impact appears to be achieved through rapid supination of the forearm up to, and including, the ball impact. What is not clear from the analysis are the reasons for the variability of ball spin rates within the data of the participant. Much of this variability may be accounted for by the type of impact between the ball and the strings of the racket.

7.3.2 – PARTICIPANT 19

Participant 19 was able to produce over 2000 rev.min^{-1} in each of the five topspin trials recorded, playing a double-handed backhand. This was comfortably above the mean ball spin rate achieved with this backhand grip, and therefore provides an interesting case study. Table 7.3 presents the key predictors of ball spin rates resulting from backhand kinematics, illustration of the accompanying technique is also presented (Figure 7.3).

The racket kinematics of participant 19 are consistent with those predicted by the regression models to produce high ball spin rates. The upward racket velocity and inclination are above the group mean, and the angle of the racket to the horizontal at impact suggests that the upward movement of the racket occurs late in the forward swing (Table 7.3).

The large upward vertical velocity of the racket at impact is due to the corresponding upward movement of the arm, particularly the forearm. However, this upward movement is as a result of different stroke kinematics than observed for the single-handed example of participant 5. Hip extension of the rear lower limb helps to drive the player forward and upwards, but this action is later in the forward swing than observed for participant 5. Therefore, this later movement may play a larger contribution in increasing the upward velocity of the arms towards ball impact. The major difference in technique, however, is the in the action of the arms. Firstly, the arms extend at the elbow, which lowers the racket-head position, before rapid flexion later in the forward swing to accelerate the arms and racket upwards through ball impact. The rapid flexion is also accompanied by a concurrent abduction at the shoulder that also helps to raise the racket-head position (Figure 7.3). There is considerably less supination velocity of this participant, and double-handed players in general, throughout the forward swing. It seems likely that both arms work together to produce the desired inclination of the racket-head through to impact.

Table 7.3 – Selected raw data for the double-handed topspin backhand of participant 19 and the group mean of all participants with a double-handed stroke.

Trial	Ball Spin rate (rev.min^{-1})	Vertical Racket Velocity (m.s^{-1})	Upward Racket Displacement (m)	Racket Angle (°)	Racket Inclination (°)	Vertical Forearm Velocity (m.s^{-1})	Vertical Upper Arm Velocity (m.s^{-1})	Elbow Flexion Velocity (°.s^{-1})	Forearm Supination Velocity (°.s^{-1})	External rotation velocity of upper arm (°.s^{-1})	Hip Extension (°)
1	2779.17	9.92	0.22	35.41	10.54	2.51	1.76	496.57	292.15	479.95	62.12
2	2212.50	11.11	0.33	34.22	11.65	2.28	1.06	439.25	96.56	435.78	45.61
3	2129.17	9.22	0.20	25.00	16.43	2.25	1.31	424.93	386.30	173.93	50.03
4	2041.67	10.67	0.27	32.45	12.42	1.65	0.44	442.94	122.52	558.65	49.30
5	2179.17	10.92	0.29	37.80	12.99	2.15	0.75	290.45	261.06	412.21	51.04
Group Mean	1309.20	7.92	0.27	30.80	8.34	1.54	0.73	358.84	254.35	281.90	31.80

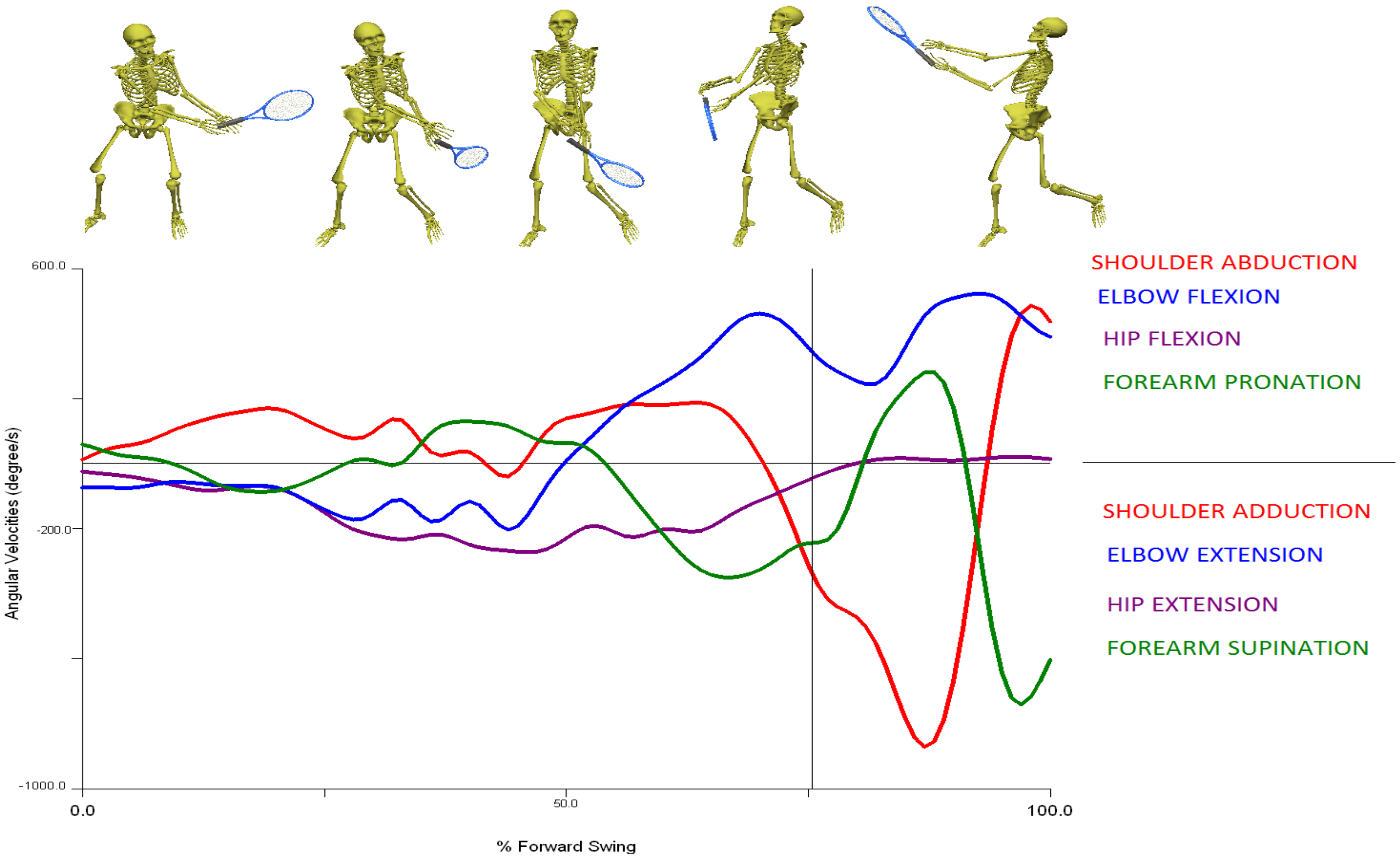


Figure 7.3 – Selected angular velocities in the forward swing during a double-handed backhand. Shoulder abduction-adduction is calculated from the position of the upper arm relative to the trunk. Forearm pronation-supination is relative to the upper arm.

The predictors of ball spin rate identified in the previous chapter were responsible for producing the increased ball spin rates produced by participant 19, using a double-handed backhand grip. Alongside the increased upward velocity of the arms, elbow flexion velocity was identified as a key variable for producing high upward racket velocities. Based on the analysis of this participant, it seems that this action may be more important for the double-handed stroke. As with the previous cases in this analysis, it was not possible to identify the cause of the variation within the results of participant 19. Again, this variation is most likely due to the types of racket-ball impact.

7.4 SUMMARY

The analysis presented here has examined the stroke technique of three participants consistently able to produce high ball spin rates when playing topspin strokes. The investigation has examined each case within the context of the results of the previous two chapters. Regardless of the type of stroke, the main predictors of high ball spin rates matched with the results for each individual participant. However, the reasons for the variation in spin rate within each participant could not be identified. Furthermore, a comparison of the single- and double-handed backhand strokes has confirmed the analysis in Chapter 5.4.2 that different kinematic patterns are responsible for producing the optimal racket kinematics at racket-ball impact. Different forehand techniques may equally be able to produce large amounts of topspin. However, this analysis has confirmed that the variables identified in chapters 5 and 6 as being important for topspin production apply to the individual and individual techniques have been examined that may help the player to maximise these variables.

Chapter 8 draws some conclusions from the results of these case analyses, and the analyses in chapters 5 and 6. Specific recommendations to players and coaches are made, and future directions for research into this area are identified.

8. CONCLUSIONS AND FURTHER WORK

8.1 CONCLUSIONS

This investigation aimed to establish which kinematic variables, or combination of kinematic variables, are responsible for producing the highest amount of ball spin resulting from tennis groundstrokes. To achieve this aim, methods of measurement capable of quantifying the anatomical rotations at joint sites and the spin rate of a tennis ball in flight were developed (Chapter 3). From this basis, differences between flat and topspin strokes were identified for the forehand and the backhand (Chapter 5), the key predictors of high ball spin rates were identified (Chapter 6) and these results were investigated in the context of individual players (Chapter 7).

The collated results of each analysis identified that increasing upward racket velocity at impact coupled with a closed racket-head inclination were the strongest determinants of high ball spin in the forehand and backhand strokes. In order to achieve these desirable racket kinematics, players must be able to bring the racket from a low to a high position in the later phases of the forward swing, increasing the upward velocity of the arm towards ball impact. This investigation has shown that the way in which this swing pattern is achieved can vary, not only between forehand and backhand, but within these strokes too. Therefore, the patterns identified within the case studies are models of successful technique, but they are not the only method by which desirable racket kinematics can be achieved. Consequently, this analysis does not attempt to prescribe an optimum model of technique for all players to mimic, however key levels of performance are identified that players should seek to achieve through their own techniques.

It is important to recognise the context of the results presented in the previous three chapters. They are more revealing collectively than taken in isolation. The differences observed between the flat and topspin strokes (Chapter 5.3) are not the only cause of variation observed in ball spin rate. Often, these differences are as a consequence of alterations elsewhere in the kinetic chain. For example, it is impossible to increase the vertical velocity of the forearm, without increasing the vertical velocity of the upper arm.

Furthermore, not all participants produced high spin rates when playing a topspin stroke, so not all differences in kinematics necessarily led to increased ball spin. The analysis that followed attempted to identify which of these differences was related to high ball spin rates (Chapter 6). Variables were identified as significant predictors of ball spin rate based on their ability to explain some unique variation in the spin rate. So, if two variables strongly correlated with ball spin rate, but also with each other, then it was likely that only one of them was considered to be a significant predictor. It should be noted that a variable which is not a significant predictor may still be important. For example, regardless of stroke, the upward velocity of the racket was the strongest predictor of ball spin rate when only racket kinematics were considered. When only human kinematics were considered, it was the upward velocity of the forearm that was the strongest predictor. However, when the ball spin rate was predicted from a combination of racket and human kinematics only the upward velocity of the racket was retained as a reliable predictor. The upward velocity of the forearm was still important to the stroke, and this was confirmed when it emerged as the strongest predictor of the upward velocity of the racket. The individual case analyses investigated the results of the preceding chapters in the context of individual players. The strongest predictors of ball spin and upward racket velocity were shown to relate well in each case presented. Therefore, the case studies supported the finding that players seeking to produce large amounts of topspin should have a high upward velocity and closed inclination of the racket at ball impact. It also showed that high upward velocities of the arm were required to achieve this. The method by which that high upward velocity of the arm was achieved did vary between each stroke analysed, and the variation between participants in the investigation suggests that a variety of techniques could achieve the same end result.

Interestingly, the variability of ball spin rate between individual experimental trials within the case analyses could not be accounted for by the variables investigated. It is possible that the relationship between ball spin rate and the variables that were found to be strong predictors is only linear to a point. There may be a critical point whereby ball spin rate is not increased by these variables, this is certainly true of the inclination of the racket-head to the vertical. To take an extreme example, once this angle tends towards 90°, the racket-head will be parallel to the court surface and the ball will contact the edge of the frame. However the point at which an effective contact of the ball on the strings can be made, may arrive at an inclination much closer to the vertical. Knudson (1991) suggested this angle should be near vertical, with an inclination of approximately 7°. The players with high spin rates in the present study had inclinations of approximately 15°, but this might be close to the optimal value. The optimal value is likely to be determined by the mechanics of the impact between racket and ball, and it is possible that much of the unexplained variation in spin (Forehand 37 %, Backhand 28 %) is accounted for by the nature of this impact. The optimal angle of contact between racket and ball suggested by Cross (2002a) is 40°, where 90° represents ball contact perpendicular to the strings. This angle depends on the relative angles and velocities of the racket and ball at the point of impact. The relative velocity increases when the ball is dropping, making it easier to impart topspin if this is the case. Information regarding the conditions of the ball pre-impact may explain some of the variation that is unexplained by the model.

8.2 LIMITATIONS

In addition to the variation of ball spin rate explained and unexplained by the regression models, there is also variation due to errors in the measurements used. A tolerance of 10 % error was made for the spin rate of the ball in a repeatability test following digitisation of the video data. Therefore, for an average topspin forehand trial, an error of up to 152 rev.min^{-1} might be reasonably expected, with a maximum error of 353 rev.min^{-1}. In reality, the error was less than this for the majority of trials, but the mean error is of a similar magnitude as some of the coefficients of the predictor variables, and should be considered if predictions of ball spin are made based on the models in chapter 6. It should also be noted that the spin calculated from a series of two-dimensional images is not purely topspin. It is likely that the majority is topspin, but there will be some lateral spin included in these calculations. The only method by which the spin axis can be isolated is to capture the spin of the ball in three-dimensions, and to define axes on the ball with respect to the laboratory or measurement volume. To date, only Sakurai *et al*. (2007) have attempted to define axes on a spinning tennis ball, but this was achieved using reflective markers attached to the ball that will themselves have affected the spin due to the impact characteristics and their mass.

There are also some errors in the measurement of joint angles and velocities calculated from the three-dimensional capture system, though these are likely to be small in comparison to the video data. The principle sources of error in motion capture are the detection of the centroid of a marker, the accuracy of marker placement on anatomical landmarks, the movement of soft tissue under a distribution of markers relative to the underlying bone, and the calculation of angles from the second and third rotations of a Cardan/Euler sequence (Cappozzo *et al*., 2005). A number of investigations attempted to quantify this error, and minimise it to a suitable magnitude (Chapter 3). The mean error in a forearm pronatory-supinatory movement was found to be 3°, and this was considered to be an error resulting from the propagation of each source outlined above. As this error was calculated from the third rotation of the Cardan 'XYZ' sequence, it may be considered to be indicative of a large error in comparison to angles calculated about the flexion-extension axis (Cappozzo *et al*., 2005). This level of error was less than the angular differences identified in Chapter 5.3, and is not of a magnitude to be considered anatomically significant in the context of the groundstrokes investigated in the present study.

There are also some limitations based on the body segments from which these angles are derived. The axial rotation of the trunk itself has previously been identified as a key factor in bringing the racket forward towards the ball, but this rotation does not play a role in raising the arm and was not considered an important factor to investigate in relation to topspin. Actions at the shoulder complex are responsible for this, but were not modelled due to the difficulty in accurately quantifying the movement of the scapula due to the movement of soft tissue. Therefore, whilst abduction of the arm at the shoulder was considered in relation to the upward movement of the arm, it is likely that elevation of the scapula could also support this. The arm cannot abduct at the shoulder by more than 90° without elevation of the scapula (Totora and Grabowski, 2000), and whilst this amount of abduction was not present in the current investigation that does not mean that scapular elevation might have played a role in abducting the arm. Therefore, modelling the movement of the arm relative to the trunk does limit the accuracy of measures at this joint, but the alternative of modelling the scapula introduces large errors due to the excessive movement of the overlying tissue in relation to the bone (Cutti *et al*., 2005). The modelling of the hip joint was not achieved by validated means, and is therefore also a limitation. The potential error in location of the hip joint centre using this method is unlikely to significantly affect sagittal plane kinematics, but will affect calculations out of this plane (Della Croce *et al*., 2005). Therefore, this method should not be used to calculate abduction or internal rotation at this joint.

The mean amount of ball spin achieved by the participants when playing a topspin stroke was lower than that previously measured (Goodwill *et al*., 2007). With reference to the participants identified in the previous chapter that were able to produce large amounts of ball spin, this suggests that many of the participants were not capable of high spin rates. This discrepancy in ability in this regard provided a large amount of variation in the spin rate that enabled key predictors of high ball spin rates to be identified. However, the limited number of participants capable of high spin rates has not enabled a number of models of successful technique to be identified.

The laboratory conditions may be, partly, responsible for the low spin rates recorded by the cohort in comparison with previous measures. The positioning of the ball machine was optimised for each player so that they could receive a ball at approximately waist height. However at this height, it would be more difficult for players with a western forehand grip to generate topspin. It was not possible to increase this height further, as the ball tended to slide off the surface of the laboratory floor. Laboratory conditions also create alien conditions for players, however these conditions were generally more of an advantage than a limitation. There are a variety of types of groundstroke that can be played from a number of positions on the court and this analysis managed to limit this variability to provide experimental trials that were consistent with each other.

8.3 FURTHER WORK

The present study was able to identify key kinematic variables associated with the production of ball spin resulting from topspin strokes. However, the variation in spin rate within participants producing higher values of topspin was not fully explained. Future work should seek to engage a number of participants capable of high ball spin production, and aim to establish the cause of the unexplained variation in the present study. It is suggested that 2000 rev.min^{-1} should be the threshold for recruitment to such an investigation, as the larger residuals observed in the regression models in the present study were related to ball spin rates above this level.

It would be beneficial for future work in this area to include information regarding the impact mechanics between the racket and ball. This should encompass the angle, spin rate and velocity of the ball prior to impact with the racket. Determining these parameters is challenging, and might ideally include the use of multiple high-speed video camera perspectives in order to better isolate the direction of the ball spin. Jinji and Sakurai (2006) isolated the spin axis of a baseball using multiple video camera perspectives and the use of one high speed camera. However, the frame rates of 250 Hz for the high-speed camera and 60 Hz for the others, and are unlikely to be sufficient to capture the spin of a tennis ball. Currently, the most accurate method of determining the spin axis of a ball is to use carefully positioned reflective markers. However, the mass and roughness of these markers will affect the spin itself. With the current technology available, it is unlikely that this issue will be satisfactorily resolved in the near future.

The combination of advanced three-dimensional motion capture systems and sophisticated marker modelling techniques adopted in the present study have allowed the relative movement between body segments to be modelled, with six-degrees-of-freedom, to a high degree of accuracy. Furthermore, the use of lightweight, rigid marker clusters has reduced the amount of soft tissue artefact between them and the body segments. However, despite the efforts of the International Society of Biomechanics (Wu *et al.*, 2005), the anatomical frames that define body segments have not been fully established for the upper extremity. Until this can be achieved, comparisons between research studies investigating tennis strokes must be made with some caution. The present study made some simplifications when modelling the trunk segment and the shoulder complex. The movement at the shoulder was defined by the relative motion of the upper arm in relation to a single trunk segment. This is a common simplification of this movement (Wu *et al.*, 2005), but the movement of the scapula, in particular, may be important in driving the upward movement of the arm and the racket. Future work should seek to resolve this issue, not only for the benefit of investigations into tennis strokes, but also wider upper extremity research.

The current work was constrained by analysing only the racket with respect to the forearm. Relative movement between these segments can quite reasonably be considered to be the result of rotations at the wrist, but do not describe the nature of these rotations. If future studies are able to accurately model the movement of the hand this will enable a full description of wrist kinematics. This may then allow questions regarding the suitability of a variety of tennis grips to be answered more fully than current analyses have allowed.

8.4 RECOMMENDATIONS TO PLAYERS AND COACHES

The combination of analyses has revealed key principles of technique related to producing higher ball spin rates when playing topspin strokes. The key findings in relation to the movement of the racket, were that a high upward velocity, closed racket-head inclination and a low-to-high trajectory in the forward swing were essential to produce higher ball spin rates. The case studies of successful technique revealed that an upward velocity of 10 $m.s^{-1}$, and a racket-head inclination of approximately 15° were recorded for strokes of 2000 rev.min^{-1} and above. To achieve this, a steep trajectory of the racket was required, though not at the expense of forward velocity towards the ball. These racket kinematics require a rapid upward movement of the forearm, though the relative movement of the upper arm is dependent on technique and most likely the type of grip used. The correct orientation of the racket-head should be controlled by rapid rotation of the forearm just prior to impact. The upward movement should be driven initially by extension of the lower limb, with the present study finding the hip to be the main contributor to this action. These factors hold true for each stroke analysed, however some differences exist depending on the stroke and the technique used. Players with a more compact technique, whereby the arm is closer to the body during the swing, should aim to rapidly flex the forearm at the elbow prior to impact. For players moving their arm as a single unit, rapid movement at the shoulder is imperative.

The key factors for all strokes are summarised below;

- High upward velocity of the racket at impact
- Low-to-high racket trajectory in the later phase of the forward swing
- Closed racket-head inclination at impact
- High upward velocity of the forearm
- Initial upward movement driven by extension at the hip joint

Each of these recommendations can be achieved through a variety of techniques and grips, and can apply to the forehand and backhand strokes. This investigation did not find clear benefits of one type of technique over another, and therefore suggest that it is up to the coach and player to implement these recommendations within their own style rather than dramatically remodel the way they play. It should also be noted that these recommendations are for the production of topspin and consideration must also be given to the forward motion of the stroke. The racket angles to the horizontal (25-30°), given in the case studies chapter, show that this was not sacrificed in producing spin by the players participating in this investigation.

The recommendations here may be used to make technical changes to a players stroke, or to identify players that might be able to produce large amounts of topspin in their groundstrokes.

8.5 SUMMARY

This investigation has made an original contribution to the knowledge of tennis groundstrokes by identifying the key kinematic variables associated with the production of topspin. This analysis has gone beyond previous studies by explicitly linking the amount of topspin produced with key joint rotations. Therefore, this investigation has not only identified key variables, but has also quantified their importance to each stroke. For example, the upward velocity of the racket at impact was shown to increase ball spin more than any other variable. This previously unreported information provides coaches with specific guidelines relating to the production of topspin in the tennis groundstrokes. This can be used for the early identification of elite players able to produce topspin, and gives important information for any possible technical changes which a player may wish to try to achieve higher performance.

In achieving the intended aim of the investigation, a number of methodological challenges were overcome. This was the first laboratory-based study to accurately quantify the spin rate of a tennis ball. This allowed this investigation to go beyond previous analyses by not only analysing topspin strokes, but the amount of topspin that was produced by each participant. It is hoped that future investigations will be able to utilise and improve upon this methodology in order to reduce the error associated with this technique and to allow the spin to be quantified in a number of axes. This was also the first study to measure tennis groundstrokes with a 6-degrees-of-freedom approach to the description of joint movement. The marker sets used in previous analyses did not permit this accurate description of joint movement, therefore the importance of some joint rotations may have been assessed erroneously. Future investigations should strive to develop this rigorous description in their work, particularly in the quantification of movement in the upper trunk. This would represent a further contribution to the work presented here.

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APPENDICIES

APPENDIX A – PUBLICATIONS RELATING TO THE THESIS

Protheroe, L., Nunn, J., Fewtrell, D. and Richards, J. (2006). Quantifying axial rotations of the upper extremity. In the proceedings of: XXIV International Symposium of Biomechanics in Sport, p.550.

QUANTIFYING AXIAL ROTATIONS OF THE UPPER EXTREMITY

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KEY WORDS: axial rotation, calibrated anatomical systems technique.

INTRODUCTION: The calibrated anatomical systems technique (CAST) (Cappozzo et al, 1995) is an established method for gait and lower limb analyses. Its application to 6-degrees-of-freedom kinematic analyses and reduction of soft tissue artefact could make it particularly useful in quantifying axial rotation of the upper extremity. Such rotations have been established as being important in generating racket-head velocity in a variety of racket sports (Marshall and Elliott, 2000). The present study assesses the accuracy of CAST in quantifying the rotation of the forearm.

METHOD: The accuracy of CAST in quantifying axial rotation was compared with a goniometer. One subject (age 22; mass 80 kg; height 1.8 m) performed 5 isolated forearm rotations of 90°. The subject sat at a table with their forearm resting on it in a fully internally rotated position. This was set as ‘zero’. The elbow remained flexed at an approximate orientation of 90° to isolate the rotation of the forearm from that of the humerus. One arm of a goniometer was attached to a table whilst the other arm was attached to the heads of the second and third metacarpals. These landmarks have limited movement relative to the forearm about the longitudinal axis. The subject externally rotated the forearm whilst maintaining a stationary elbow position throughout. The rotation was simultaneously captured with a seven camera motion capture system (Qualisys, Sweden) operating at 240 Hz. The rotation of the forearm was determined relative to the humerus using rigid clusters of four non-colinear markers. The forearm cluster was placed at the most distal point possible. The forearm was defined proximally by the medial and lateral epicondyles of the humerus and distally by the styloids of the radius and ulna whilst the humerus was defined proximally by the acromion process of the scapula with a radius of 0.04 m and distally by the medial and lateral epicondyles of the humerus. Axial rotation was determined by the third rotation in the XYZ Cardan sequence using movement analysis software (Visual 3D; C-motion, USA).

RESULTS: A mean rotation of 73.23° (± 7.58) was recorded.

DISCUSSION: The underestimation of forearm rotation measured using CAST highlights the difficulties of quantifying axial rotations about the upper extremity. Measurement of the forearm is particularly difficult as it is the interaction of the radius and ulna that provide the rotation and the rotation is therefore greater at the distal end of the segment. The forearm cluster was placed at the most distal point practically possible but rotation of this segment may be better estimated by considering the relative rotations of the humerus, forearm and hand. Soft tissue artefact has been highlighted as being reduced by CAST (Cappozzo et al., 1995) but this effect was still observed and quantification of this effect could provide further accuracy to this method.

CONCLUSION: The axial rotation of the forearm was underestimated by the CAST method but could still prove to be an effective method if the limitations highlighted here are addressed.

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APPENDIX B – CONSENT AND SCREENING FORMS

University of Central Lancashire

Information Sheet and Consent Form

Title of study:
Biomechanical Analysis of Different Tennis Strokes

Aim of study:
To investigate the movement of your body in relation to how much topspin you can produce in your tennis strokes.

What we will ask you to do?
Reflective markers will be attached to your body with double sided sticky tape and elastic strapping. These allow the movement of your body to be measured. You will be asked to carry out five trials of each stroke (Forehand and Backhand).

No tests will exceed either the range of movement or forces experienced in normal daily life.

All data will be coded and no names will be able to be associated with any data recorded.

The tests will last no longer than one hour and a half.

CONSENT FORM

Please initial box

1. I have read the above information and understand that my participation is voluntary and That I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐

2. I agree to take part in the above study. ☐

________________	________________	________________
Name of Participant	Date	Signature
________________	________________	________________
Parental/Guardian Consent (if participant under 16 years of age)	Date	Signature
________________	________________	________________
Researcher	Date	Signature

Sports Science Laboratories

Pre-Exercise Health Screening Questionnaire.

Before anyone takes part in an exercise program involving laboratory testing or assessment, it is the duty of the University to make sure that it is safe for him or her to do so. This is to identify and exclude people who may have medical conditions that may put them at risk when they are tested or when they exercise. This is a requirement of the University insurance policy, to comply with the legal, ethical, and health implications of human exercise testing.

This involves:

- testing for a known disease
- testing for signs and symptoms of disease
- assessing cardiac risk factors
- considering age and exercise intentions

A pre-exercise Health Screen Questionnaire adapted from the Pre-Exercise Health Screening Guide (Olds & Norton, 1999, Human Kinetics) listed below is used for all subjects or students involved in exercise testing in the Exercise Physiology Laboratory before they start exercising.

Guidelines for use

The Pre-Exercise Health Screen Questionnaire aims to provide an answer to three questions for every person screened:

- Does this person need to have a medical check-up and exercise ECG before undertaking exercise testing or an exercise program?
- Does a medical doctor need to be present during a maximal exercise test?
- Does a medical doctor need to be present during a sub-maximal exercise test?

The Pre-Exercise Health Screen Questionnaire (p.5-6) relates to a series of flowcharts that are listed subsequently. The flowcharts decide the answers to the three questions above, and provide guidelines for exercise testing. Refer to System Overview flowchart (p.7).

Stage 1 relates to known diseases. If the subject does have a known disease and any answer to this section is ‘Yes’ the subject is excluded from the test, must get a medical check-up, and a medical doctor must be present during both maximal or sub-maximal tests. Refer to Stage 1 flowchart (p.8).

If there are no known diseases, screening proceeds to Stage 2, to detect any signs or symptoms of disease. An answer ‘Yes’ to any questions in this section, the subject must be excluded from the test, must get a medical check-up, and a medical doctor must be present during both maximal or submaximal tests. Refer to Stage 2 flowchart (p.9).

If there are no signs or symptoms at stage 1 or 2, then Stage 3 and Stage 4 are completed. These assess the presence of cardiac risk factors, age, and exercise intentions (refer to Stage 3 and Stage 4 flowcharts, p.10-11).

There are 3 possible outcomes at this point:

Risk Factors	**Moderate Exercise**	**Vigorous Exercise**
> 2 cardiac risk factors	No medical check-up required. Medical doctor present for maximal tests only.	Medical check-up prior to exercise. Medical doctor present for maximal tests only.
< 2 cardiac risk factors 41 or older (male) 51 or older (female)	No medical check-up required. Medical doctor present for maximal tests only.	Medical check-up prior to exercise. Medical doctor present for maximal tests only.
< 2 cardiac risk factors 40 or younger (male) 50 or younger (female)	No medical check-up required. Medical doctor presence not required.	

If a person does need a medical check-up, no testing should be conducted or exercise program prescribed without written clearance from a medical doctor.

In the case when any data is unavailable, such as serum cholesterol and serum HDL levels, base any analysis on the known data.

Pre-Exercise Health Screening Questionnaire

A copy of the Pre-Exercise Health Screening Questionnaire is listed on the following 2 pages (adapted from the Pre-Exercise Health Screening Guide, Olds & Norton, Human Kinetics, 1999).

UCLan Sports Science Labs: Health Screen Questionnaire

Name__________________________ **Age**_________ **Gender** **M** **F**

Address____

______________________________________ **Phone**___________________

Height______________ **Weight**_______________ **Date of test** __________

Profession____

Stage 1 - Known Diseases (Medical Conditions)

1. List the medications you take on a regular basis.
2. Do you have diabetes? No Yes

   a) if yes, please indicate if it is insulin-dependent diabetes mellitus (IDDM) or non-insulin-dependent diabetes mellitus (NIDDM). IDDM NIDDM

   b) if IDDM, for how many years have you had IDDM? _________ years
3. Have you had a stroke? No Yes
4. Has your doctor ever said you have heart trouble? No Yes
5. Do you take asthma medication? No Yes
6. Are you or do you have reason to believe you may be pregnant? No Yes
7. Is there any other physical reason that prevents you from participating in an exercise program (e.g. cancer; osteoporosis; severe arthritis; mental illness; thyroid, kidney or liver disease)? No Yes

Stage 2 - Signs and Symptoms

8. Do you often have pains in your heart, chest, or surrounding areas, especially during exercise? No Yes
9. Do you often feel faint or have spells of severe dizziness during exercise? No Yes
10. Do you experience unusual fatigue or shortness of breath at rest or with mild exertion? No Yes
11. Have you had an attack of shortness of breath that came on after you stopped exercising? No Yes
12. Have you been awakened at night by an attack of shortness of breath? No Yes

13. Do you experience swelling or accumulation of fluid in or around your ankles? No Yes

14. Do you often get the feeling that your heart is beating faster, racing, or skipping beats, either at rest or during exercise? No Yes

15. Do you regularly get pains in your calves and lower legs during exercise which are not due to soreness or stiffness? No Yes

16. Has your doctor ever told you that you have a heart murmur? No Yes

Stage 3 - Cardiac Risk Factors

17. Do you smoke cigarettes daily, or have you quit smoking within the past two years? No Yes

    If yes, how many cigarettes per day do you smoke (or did you smoke in the past two years)? _________ per day

18. Has your doctor ever told you that you have high blood pressure? No Yes

19. Has your father, mother, brother, or sister had a heart attack or suffered from cardiovascular disease before the age of 65? No Yes

    If yes,

    a) Was the relative male or female? ________________

    b) At what age did he or she have the stroke or heart attack? ________________

    c) Did this person die suddenly as a result of the stroke or heart attack? No Yes

20. Have you experienced menopause before the age of 45? No Yes

    If yes, do you take hormone replacement medication? No Yes

If known, enter blood pressure and blood lipid values:

21. What is your systolic blood pressure? __________mmHg

22. What is your diastolic blood pressure? __________mmHg

23. What is your serum cholesterol level? ______mmol/L or mg/dL

24. What is your serum HDL level? ______mmol/L or mg/dL

25. What is your serum triglyceride level? ______mmol/L or mg/dL

Stage 4 - Exercise Intentions

26. Does your job involve sitting for a large part of the day? No Yes

27. What are your current activity patterns?

a) Frequency: ______exercise sessions per week

b) Intensity: Sedentary Moderate Vigorous

c) History: <3 months 3-12 months >12 months

d) Duration: ______minutes per session

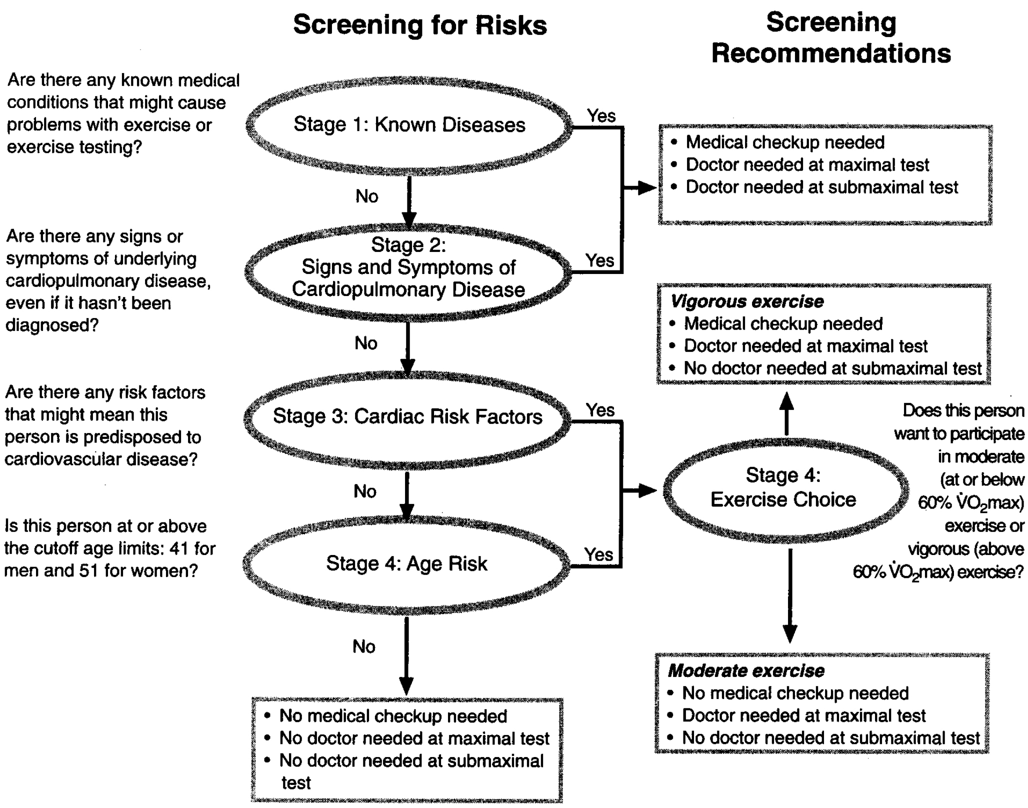
28. What types of exercises do you do?

29. Do you want to exercise at a moderate intensity (e.g. brisk walking) or at a vigorous intensity (e.g. jogging)? Moderate Vigorous

I acknowledge that the above information is correct to the best of my knowledge.

Sign: ________________________________ Date: ___________________

System overview



Stage 1: known disease

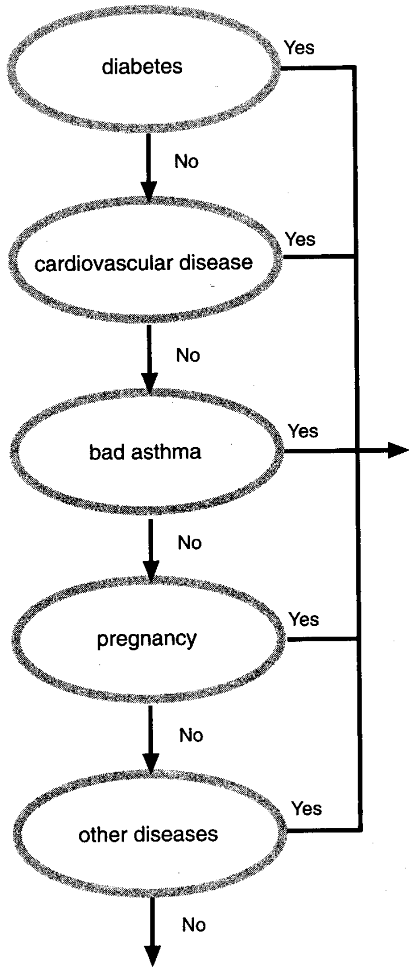
Diabetes counts as a disease if
- this person has IDDM **and** either is > 30 **or** has had IDDM for >15 years **or**
- the subject has NIDDM and is > 35.

A person has cardiovascular disease if
- he has had a stroke **or**
- a doctor has told him he has heart disease **or**
- he is taking cardiovascular medication.

A person has bad asthma if
- she is taking asthma medication **and**
- she answers "Yes" when asked if she suffers from dyspnea or shortness of breath.

A person is classified as pregnant if
- she knows she is pregnant **or**
- she has reason to believe she may be pregnant.

A person is considered to have other diseases if he suffers from liver or kidney disease or other diseases that might prevent him from undertaking physical activity.



- This person **does** need a medical checkup and exercise ECG before testing or exercise.
- A **medical doctor** must be present during a maximal test.
- A **medical doctor** must be present during a submaximal test.

Proceed to Stage 2: Signs and Symptoms

Stage 2: signs and symptoms of disease

Does the subject often have pains in her heart and chest, especially during exercise?

Has the subject at any time in the last 12 months had an attack of shortness of breath that came on during the day when he was not doing anything strenuous?

Does the subject often feel faint or have spells of severe dizziness?

Has the subject had an attack of shortness of breath after exercising at any time in the last 12 months? **or** has he at any time in the last 12 months been awakened at night by an attack of shortness of breath?

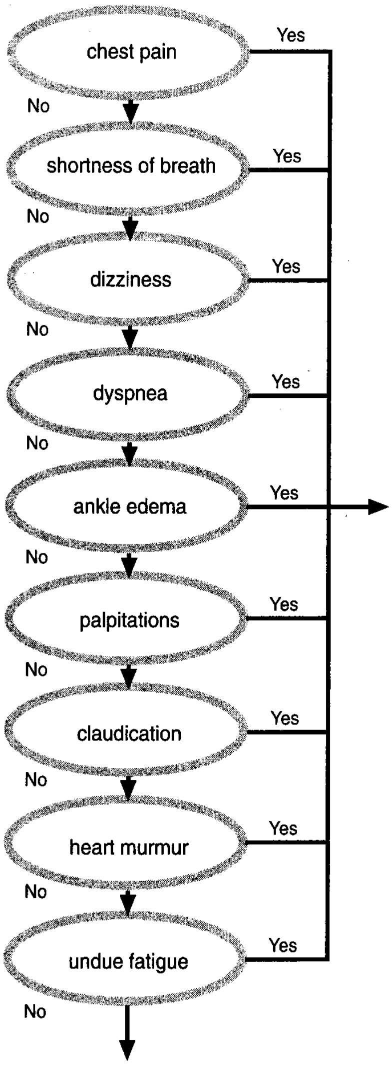
Does the subject experience swelling or accumulation of fluid in her ankles?

Does the subject often get the feeling that his heart is beating faster, racing, or skipping beats?

Does the subject regularly get pains in her calves and lower legs during exercise which are not due to soreness or stiffness?

Has the subject's doctor ever told him that he has a heart murmur?

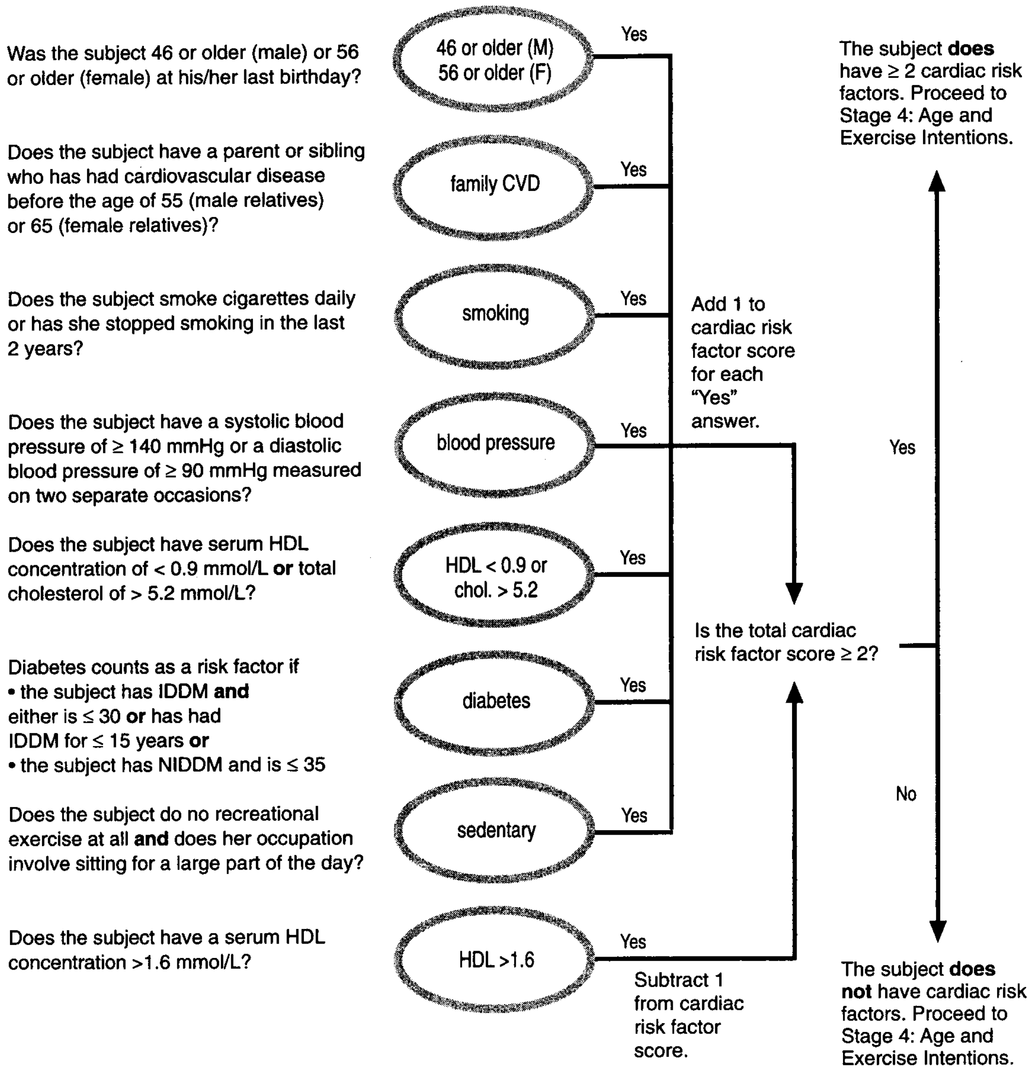
Does the subject experience undue fatigue with usual activities?



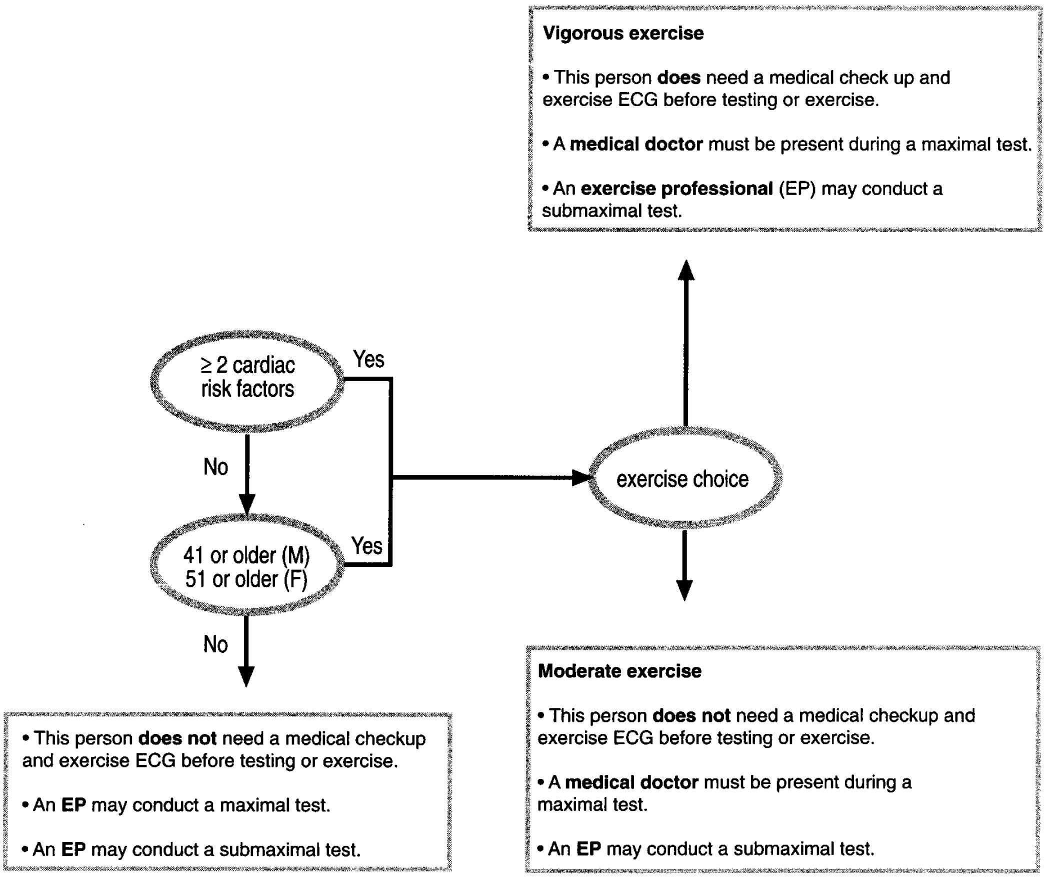
- The subject **does** need a medical checkup and exercise ECG before testing or exercise.
- A **medical doctor** must be present during a maximal test.
- A **medical doctor** must be present during a submaximal test.

Proceed to Stage 3: Cardiac Risk Factors

Stage 3: cardiac risk factors



Stage 4: age and exercise intentions



APPENDIX C – STATISTICAL TABLES

Appendix C1 – Normality Tests

Table C1 - Normality tests of forehand variables.

Variable	95 % CI Of Skewness	95 % CI Of Skewness	Kolmogorov-Smirnov Test	Decision
	Crosses Zero (Y/N)	Crosses Zero (Y/N)	P value	
Ball Spin Rate	Y	Y	> 0.05	Normal – use t-test
Vertical Racket Velocity	Y	Y	> 0.05	Normal – use t-test
Racket Inclination	Y	Y	> 0.05	Normal – use t-test
Racket Velocity Vector	Y	N	< 0.05	Not normal – use Wilcoxon
Racket Angle	Y	N	> 0.05	Normal – use t-test
Racket Upward displacement	Y	Y	> 0.05	Normal – use t-test
Racket Upward displacement pre-impact	N	Y	< 0.05	Not normal – use Wilcoxon
Upward Racket w.r.t forearm	N	N	< 0.05	Not normal – use Wilcoxon
Upward Racket w.r.t forearm velocity	Y	N	> 0.05	Not normal – use Wilcoxon
Vertical Forearm Velocity	Y	Y	> 0.05	Normal – use t-test
Upper arm vertical velocity	Y	Y	> 0.05	Normal – use t-test
Upper arm axial rotation	Y	N	< 0.05	Not normal – use Wilcoxon
Upper arm rotation velocity	Y	N	< 0.05	Not normal – use Wilcoxon
Shoulder Abduction	Y	N	> 0.05	Normal – use t-test
Shoulder Abduction Velocity	Y	N	< 0.05	Not normal – use Wilcoxon
Forearm Pronation	Y	Y	> 0.05	Normal – use t-test
Forearm Pronation Velocity	Y	Y	> 0.05	Normal – use t-test
Elbow Flexion	N	N	< 0.05	Not normal – use Wilcoxon
Elbow Flexion Velocity	N	N	> 0.05	Not normal – use Wilcoxon
Hip Flexion	Y	Y	> 0.05	Normal – use t-test
Hip Flexion Velocity	Y	N	< 0.05	Not normal – use Wilcoxon
Knee Flexion	Y	Y	> 0.05	Normal – use t-test
Knee Flexion Velocity	N	N	< 0.05	Not normal – use Wilcoxon

Table C2 - Normality tests of backhand variables.

Variable	95 % CI Of Skewness	95 % CI of Skewness	Kolmogorov-Smirnov Test	Decision
	Crosses Zero (Y/N)	Crosses Zero (Y/N)	P value	
Ball Spin Rate	N	Y	< 0.05	Not normal – use Wilcoxon
Vertical Racket Velocity	N	Y	> 0.05	Normal – use t-test
Racket Inclination	Y	Y	> 0.05	Normal – use t-test
Racket Velocity Vector	Y	Y	> 0.05	Normal – use t-test
Racket Angle	Y	Y	> 0.05	Normal – use t-test
Racket Upward displacement	Y	N	< 0.05	Not normal – use Wilcoxon
Racket Upward displacement pre-impact	N	N	< 0.05	Not normal – use Wilcoxon
Upward Racket w.r.t forearm	N	Y	> 0.05	Normal – use t-test
Upward Racket w.r.t forearm velocity	N	N	< 0.05	Not normal – use Wilcoxon
Vertical Forearm Velocity	N	Y	< 0.05	Not normal – use Wilcoxon
Upper arm vertical velocity	N	Y	< 0.05	Not normal – use Wilcoxon
Upper arm axial rotation	N	Y	< 0.05	Not normal – use Wilcoxon
Upper arm rotation velocity	N	N	< 0.05	Not normal – use Wilcoxon
Shoulder Abduction	N	Y	< 0.05	Not normal – use Wilcoxon
Shoulder Abduction Velocity	N	Y	> 0.05	Normal – use t-test
Forearm Pronation	N	N	< 0.05	Not normal – use Wilcoxon
Forearm Pronation Velocity	N	N	< 0.05	Not normal – use Wilcoxon
Elbow Flexion	N	N	< 0.05	Not normal – use Wilcoxon
Elbow Flexion Velocity	N	Y	< 0.05	Not normal – use Wilcoxon
Hip Flexion	N	N	< 0.05	Not normal – use Wilcoxon
Hip Flexion Velocity	Y	Y	> 0.05	Normal – use t-test
Knee Flexion	Y	Y	> 0.05	Normal – use t-test
Knee Flexion Velocity	Y	Y	> 0.05	Normal – use t-test

Appendix C2 – Statistical differences between flat and topspin strokes

Appendix C2.1 - Forehand Comparisons

Table C3 – T-test for forehand comparisons of flat and topspin strokes (degrees-of-freedom = 82)

Variable	**T-value**	**P-value**
Ball Spin rate	9.86	< 0.001
Vertical racket velocity	12.33	< 0.001
Racket Inclination	7.65	< 0.001
Racket Velocity	3.90	< 0.001
Racket Angle	9.75	< 0.001
Vertical Racket trajectory	2.86	0.006
Vertical racket pre-impact	7.95	< 0.001
Upward racket w.r.t. forearm	0.98	0.331
Upward racket w.r.t. forearm velocity	2.42	0.024
Vertical Forearm Velocity	8.71	< 0.001
Forearm Pronation	2.26	0.027
Forearm Pronation Velocity	1.87	0.065
Elbow Flexion	1.31	0.195
Elbow Flexion Velocity	3.30	0.001
Vertical upper arm velocity	7.72	< 0.001
Upper arm rotation	5.00	< 0.001
Upper arm rotation velocity	0.54	0.589
Shoulder abduction	0.78	0.440
Shoulder abduction velocity	2.44	0.017
Hip Flexion	3.57	0.001
Hip Flexion Velocity	2.31	0.024
Knee Flexion	4.16	< 0.001
Knee Flexion Velocity	2.24	0.028

Table C4 – Wilcoxon test for forehand comparisons of flat and topspin strokes (degrees-of-freedom = 82)

Variable	**Z-value**	**P-value**
Ball Spin rate	7.10	< 0.001
Vertical racket velocity	7.78	< 0.001
Racket Inclination	6.13	< 0.001
Racket Velocity	3.56	< 0.001
Racket Angle	7.56	< 0.001
Vertical Racket trajectory	2.77	0.006
Vertical racket pre-impact	6.59	< 0.001
Upward racket w.r.t. forearm	1.35	0.178
Upward racket w.r.t. forearm velocity	2.41	0.016
Vertical Forearm Velocity	6.93	< 0.001
Forearm Pronation	2.07	0.038
Forearm Pronation Velocity	1.94	0.053
Elbow Flexion	1.02	0.308
Elbow Flexion Velocity	3.51	< 0.001
Vertical upper arm velocity	6.32	< 0.001
Upper arm rotation	4.57	< 0.001
Upper arm rotation velocity	0.54	0.587
Shoulder abduction	0.66	0.509
Shoulder abduction velocity	1.91	0.056
Hip Flexion	3.21	0.001
Hip Flexion Velocity	2.42	0.016
Knee Flexion	3.98	< 0.001
Knee Flexion Velocity	1.22	0.224

Appendix C2.2 - Backhand Comparisons

Table C5 – T-test for backhand comparisons of flat and topspin strokes (degrees-of-freedom = 85)

Variable	**T-value**	**P-value**
Ball Spin rate	10.07	< 0.001
Vertical racket velocity	12.00	< 0.001
Racket Inclination	4.46	< 0.001
Racket Velocity	2.47	0.015
Racket Angle	9.46	< 0.001
Vertical Racket trajectory	4.21	< 0.001
Vertical racket pre-impact	7.28	< 0.001
Upward racket w.r.t. forearm	1.35	0.180
Upward racket w.r.t. forearm velocity	1.21	0.229
Vertical Forearm Velocity	8.24	< 0.001
Forearm Pronation	3.24	0.002
Forearm Pronation Velocity	1.38	0.170
Elbow Flexion	1.46	0.147
Elbow Flexion Velocity	2.98	0.004
Vertical upper arm velocity	4.01	< 0.001
Upper arm rotation	1.15	0.255
Upper arm rotation velocity	0.42	0.679
Shoulder abduction	0.13	0.899
Shoulder abduction velocity	1.69	0.095
Hip Flexion	6.15	< 0.001
Hip Flexion Velocity	0.49	0.623
Knee Flexion	1.56	0.123
Knee Flexion Velocity	0.43	0.670

Table C6 – Wilcoxon test for backhand comparisons of flat and topspin strokes (degrees-of-freedom = 85)

Variable	**Z-value**	**P-value**
Ball Spin rate	7.23	< 0.001
Vertical racket velocity	7.71	< 0.001
Racket Inclination	4.18	< 0.001
Racket Velocity	2.47	0.013
Racket Angle	6.99	< 0.001
Vertical Racket trajectory	3.78	< 0.001
Vertical racket pre-impact	6.24	< 0.001
Upward racket w.r.t. forearm	1.10	0.273
Upward racket w.r.t. forearm velocity	1.79	0.074
Vertical Forearm Velocity	6.41	< 0.001
Forearm Pronation	2.79	0.005
Forearm Pronation Velocity	1.29	0.197
Elbow Flexion	1.79	0.073
Elbow Flexion Velocity	2.93	0.003
Vertical upper arm velocity	3.85	<0.001
Upper arm rotation	1.05	0.295
Upper arm rotation velocity	0.06	0.950
Shoulder abduction	0.17	0.865
Shoulder abduction velocity	1.69	0.090
Hip Flexion	5.46	< 0.001
Hip Flexion Velocity	0.65	0.515
Knee Flexion	0.90	0.370
Knee Flexion Velocity	0.21	0.832

Appendix C2.3 - Backhand grip comparisons

Table C7 – Mean comparisons of single- and double-handed backhand grips when playing the topspin backhand stroke

	Single-handed	**Double-handed**
Ball Spin (rpm)	962.38 (721.77)	1306.73 (585.87)
Racket Velocity ($m.s^{-1}$)	17.20 (3.60)	16.98 (3.20)
Vertical Racket Velocity ($m.s^{-1}$)	5.95 (2.81)	7.82 (2.36)
Racket Inclination w.r.t. vertical (°)	3.05 (8.11)	7.56 (6.46)
Racket Angle w.r.t. horizontal (°)	17.72 (11.59)	30.80 (6.94)
Upward displacement of racket in forward swing (m)	-0.24 (0.47)	-0.03 (0.33)
Upward displacement of racket prior to impact (m)	0.20 (0.14)	0.27 (0.16)
Upward Racket w.r.t. forearm (°)	-12.74 (7.90)	-21.25 (11.16)
Forearm Supination (°)	26.47 (11.29)	1.73 (20.26)
Elbow Flexion (°)	-24.83 (18.70)	30.40 (12.69)
External rotation of humerus (°)	11.69 (9.77)	17.24 (11.42)
Shoulder Abduction (°)	9.50 (6.67)	10.16 (7.52)
Hip Extension (°)	28.20 (14.74)	31.77 (16.72)
Knee Flexion (°)	3.51 (21.89)	4.61 (19.01)
Upward Racket w.r.t. forearm velocity ($°.s^{-1}$)	4.80 (209.55)	-155.81 (321.34)
Forearm Supination velocity ($°.s^{-1}$)	613.35 (321.03)	255.72 (221.71)
Elbow Flexion velocity ($°.s^{-1}$)	-164.59 (286.61)	356.30 (152.42)
External rotation of humerus velocity ($°.s^{-1}$)	237.01 (207.49)	287.70 (151.75)
Shoulder Abduction velocity ($°.s^{-1}$)	61.73 (114.89)	-116.11 (158.52)
Hip Extension velocity ($°.s^{-1}$)	83.06 (90.67)	133.51 (99.21)
Knee Flexion velocity ($°.s^{-1}$)	90.57 (107.16)	99.38 (140.70)
Vertical Forearm velocity ($m.s^{-1}$)	2.85 (0.83)	1.54 (0.62)
Vertical Upper Arm velocity ($m.s^{-1}$)	1.44 (0.47)	0.75 (0.42)

Table C8 – T-test comparisons of single- and double-handed backhand grips when playing the topspin backhand stroke (equal variances not assumed).

	T-value	**p-value**
Ball Spin	2.38	0.020
Racket Velocity	0.30	0.769
Vertical Racket Velocity	3.30	0.002
Racket Inclination w.r.t. vertical	2.79	0.007
Racket Angle w.r.t. horizontal	6.05	< 0.001
Upward displacement of racket in forward swing	2.24	0.030
Upward displacement of racket prior to impact	2.29	0.025
Upward Racket w.r.t. forearm	4.27	< 0.001
Forearm Supination	7.43	< 0.001
Elbow Flexion	15.19	< 0.001
External rotation of humerus	2.45	0.017
Shoulder Abduction	0.44	0.663
Hip Extension	1.07	0.287
Knee Flexion	0.24	0.808
Upward Racket w.r.t. forearm velocity	2.90	0.005
Forearm Supination velocity	5.80	< 0.001
Elbow Flexion velocity	9.93	< 0.001
External rotation of humerus velocity	1.25	0.215
Shoulder Abduction velocity	6.22	< 0.001
Hip Extension velocity	2.49	0.015
Knee Flexion velocity	0.34	0.736
Vertical Forearm velocity	8.06	< 0.001
Vertical Upper Arm velocity	7.10	< 0.001

Table C9 – Mann-Whitney test comparisons of single- and double-handed backhand grips when playing the topspin backhand stroke

	Z-value	**p-value**
Ball Spin	2.60	0.009
Racket Velocity	0.03	0.978
Vertical Racket Velocity	2.94	0.003
Racket Inclination w.r.t. vertical	3.07	0.002
Racket Angle w.r.t. horizontal	5.22	< 0.001
Upward displacement of racket in forward swing	1.95	0.051
Upward displacement of racket prior to impact	2.04	0.041
Upward Racket w.r.t. forearm	3.74	< 0.001
Forearm Supination	6.11	< 0.001
Elbow Flexion	7.87	< 0.001
External rotation of humerus	2.23	0.026
Shoulder Abduction	0.37	0.713
Hip Extension	0.20	0.844
Knee Flexion	0.43	0.665
Upward Racket w.r.t. forearm velocity	2.29	0.022
Forearm Supination velocity	5.34	< 0.001
Elbow Flexion velocity	7.36	< 0.001
External rotation of humerus velocity	0.33	0.739
Shoulder Abduction velocity	5.00	< 0.001
Hip Extension velocity	2.08	0.038
Knee Flexion velocity	0.15	0.883
Vertical Forearm velocity	6.08	< 0.001
Vertical Upper Arm velocity	5.80	< 0.001

Appendix C3 - Regression Models

Appendix C3.1 – Forehand Regression

C.3.1.1 - Model A – Prediction of ball spin from racket kinematics

Table C10 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-343.10	336.89	
Vertical Racket Velocity	113.93*	40.09*	0.50*
Racket Inclination	21.50*	5.96*	0.23*
Racket Velocity	17.46	19.36	0.09
Racket upward trajectory	-147.74	139.32	-0.07
Racket upward trajectory pre-impact	875.71	560.60	0.13
Racket angle	3.93	10.64	0.06

R^2 = 0.63. *Variable significantly contributes to the model ($p < 0.05$).

C.3.1.2 - Model B – Prediction of ball spin from human kinematics

Table C11 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-463.68	202.95	
Upward velocity forearm	297.77*	111.42*	0.36*
Hip extension velocity	-0.42	0.33	-0.08
Elbow extension velocity	-0.05	0.26	-0.01
Shoulder abduction velocity	0.29	0.35	0.06
Forearm pronation velocity	0.45*	0.21*	0.17*
Internal rotation velocity of humerus	-0.62*	0.21*	-0.24*
Upward racket wrt forearm velocity	0.09	0.08	0.08
Upward velocity humerus	60.06	186.56	0.05
Hip extension	-11.29*	2.67*	-0.32*

$R^2 = 0.37$. *Variable significantly contributes to the model ($p < 0.05$).

Table C12 – Final model omitting influential cases

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
B1	(Constant)	250.87	131.68	
	Vertical Forearm Velocity	405.61*	55.62*	0.49*
B2	(Constant)	-5.68	146.98	
	Vertical Forearm Velocity	337.41*	57.24*	0.41*
	Hip Flexion	-8.93*	2.55*	-0.24*
B3	(Constant)	-225.67	178.87	
	Vertical Forearm Velocity	355.78*	57.31*	0.43*
	Hip Flexion	-10.95*	2.70*	-0.30*
	External Upper Arm Rotation Velocity	-0.41*	0.19*	-0.15*
B4	(Constant)	-425.96	197.74	
	Vertical Forearm Velocity	334.69*	57.38*	0.41*
	Hip Flexion	-10.87*	2.66*	-0.30*
	External Upper Arm Rotation Velocity	-0.66	0.22*	-0.24*
	Forearm Pronation Velocity	0.50*	0.22*	0.18*

Note: Model B1: $R^2 = 0.24$, Model B2: $\Delta R^2 = 0.05$ ($p < 0.05$), Model B3: $\Delta R^2 = 0.02$ ($p < 0.05$), Model B4: $\Delta R^2 = 0.02$ ($p < 0.05$). *Variable significantly contributes to the model ($p < 0.05$).

C.3.1.3 - Model C – Prediction of ball spin from racket and human kinematics

Table C13 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-225.32	140.64	
Upward racket velocity	128.69*	15.01*	0.56*
Racket inclination	22.70*	5.08*	0.25*
Upward forearm velocity	60.46	49.47	0.07
Forearm pronation velocity	-0.02	0.16	-0.01
Internal rotation of humerus	-0.31*	0.15*	-0.12*
Hip Flexion	-4.29*	1.96*	-0.12*

$R^2 = 0.63$. *Variable significantly contributes to the model ($p < 0.05$).

Table C14 – Final model omitting influential cases

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
C1	(Constant)	-72.96	90.67	
	Vertical Racket Velocity	175.12*	11.87*	0.75*
C2	(Constant)	16.14	86.98	
	Vertical Racket Velocity	149.85*	12.27*	0.64*
	Racket Inclination	23.46*	4.78*	0.26*
C3	(Constant)	-23.48	105.72	
	Vertical Racket Velocity	147.41*	12.82*	0.63*
	Racket Inclination	22.65*	4.95*	0.25*
	Hip Flexion	-1.31	1.97	-0.04
C4	(Constant)	-143.20	122.65	
	Vertical Racket Velocity	146.67*	12.73*	0.63*
	Racket Inclination	23.39*	4.93*	0.26*
	Hip Flexion	-2.75	2.10	-0.08
	External Rotation of Upper Arm Velocity	0.27	0.14	0.10

Note: Model C1: $R^2 = 0.56$, Model C2: $\Delta R^2 = 0.06$ ($p < 0.05$), Model C3: $\Delta R^2 = < 0.01$ ($p = 0.51$), Model C4: $\Delta R^2 = 0.01$ ($p = 0.06$). *Variable significantly contributes to the model ($p < 0.05$).

C.3.1.4 - Model D – Prediction of upward racket velocity from human kinematics

Table C15 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-0.10	0.82	
Upward forearm velocity	2.18*	0.45*	0.61*
Hip flexion velocity	< -0.01	< 0.01	-0.1
Elbow Flexion velocity	< 0.01	< 0.01	0.01
Shoulder abduction velocity	< 0.01	< 0.01	0.01
Forearm pronation velocity	< 0.01*	< 0.01*	0.21*
Internal rotation of humerus	< 0.01	< 0.01	0.14
Upward racket wrt forearm velocity	< 0.01	< 0.01	-0.06
Upward humerus velocity	-0.67	0.76	-0.12
Hip Flexion	-0.03*	0.01*	-0.22*

R^2 = 0.68. *Variable significantly contributes to the model ($p < 0.05$).

Table C16 – Final model omitting influential cases

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
D1	(Constant)	2.37	0.52	
	Vertical Forearm Velocity	2.08*	0.22*	0.59*
D2	(Constant)	1.35	0.58	
	Vertical Forearm Velocity	1.81*	0.23*	0.51*
	Hip Flexion	-0.04*	0.01*	-0.23*
D3	(Constant)	1.16	0.59	
	Vertical Forearm Velocity	1.71*	0.23*	0.49*
	Hip Flexion	-0.03*	0.01*	-0.20*
	Forearm Pronation Velocity	< 0.01	< 0.01	0.12
D4	(Constant)	-0.24	0.78	
	Vertical Forearm Velocity	1.74*	0.23*	0.49*
	Hip Flexion	-0.04*	0.01*	-0.26*
	Forearm Pronation Velocity	< 0.01*	< 0.01*	0.21*
	External Upper Arm Rotation Velocity	< 0.01*	< 0.01*	-0.20*

Note: Model B1: $R^2 = 0.35$, Model B2: $\Delta R^2 = 0.05$ ($p < 0.05$), Model B3: $\Delta R^2 = 0.01$ ($p = 0.07$), Model B4: $\Delta R^2 = 0.02$ ($p < 0.03$). *Variable significantly contributes to the model ($p < 0.05$).

Appendix C3.2 - Backhand

C3.2.1 - Model A – Prediction of ball spin from racket kinematics

Table C17 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	244.42	300.40	
Upward racket velocity	244.13*	52.57*	1.07*
Racket inclination	19.47*	5.20*	0.20*
Racket velocity	-18.63	18.81	-0.10
Upward racket trajectory	131.71	126.29	0.08
Upward racket trajectory pre-impact	-1049.95*	373.44*	-0.23*
Racket angle	-13.75	11.37	-0.22

R^2 = 0.72. *Variable significantly contributes to the model ($p < 0.05$).

C3.2.2 - Model B – Prediction of ball spin from human kinematics

Table C18 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-236.64	144.20	
Upward forearm velocity	563.63*	85.61*	0.84*
Hip extension velocity	0.14	0.48	0.02
Elbow Flexion	0.54	2.66	0.02
Elbow Flexion velocity	0.81*	0.20*	0.38*
Forearm supination velocity	0.67*	0.17*	0.31*
Upward humerus velocity	-601.71*	140.48*	-0.53*
Forearm supination	9.52*	2.65*	0.28*
Hip extension	12.61*	2.75*	0.30*

$R^2 = 0.46$. *Variable significantly contributes to the model ($p < 0.05$).

Table C19 – Final model omitting influential cases

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
B1	(Constant)	580.66	100.77	
	Vertical Forearm Velocity	128.41*	50.79*	0.19*
B2	(Constant)	617.678	94.38	
	Vertical Forearm Velocity	571.69*	98.74*	0.84*
	Vertical upper arm velocity	-899.67*	175.75*	-0.75*
B3	(Constant)	107.63	111.02	
	Vertical Forearm Velocity	755.64*	91.23*	1.11*
	Vertical upper arm velocity	-856.45*	155.57*	-0.71*
	Elbow Flexion Velocity	1.12*	0.16*	0.53*
B4	(Constant)	40.67	118.26	
	Vertical Forearm Velocity	706.33*	95.97*	1.04*
	Vertical upper arm velocity	-780.34*	162.10*	-0.65*
	Elbow Flexion Velocity	1.13*	0.16*	0.53*
	Forearm Pronation Velocity	-0.23	0.14	-0.10
B5	(Constant)	-164.81	134.58	
	Vertical Forearm Velocity	681.81*	94.17*	1.01*
	Vertical upper arm velocity	-784.73*	158.45*	-0.65*
	Elbow Flexion Velocity	1.12*	0.16*	0.53*
	Forearm Pronation Velocity	-0.34*	0.14*	-0.16
	Hip Flexion	-8.33*	2.79*	-0.19*
B6	(Constant)	-162.10	128.17	
	Vertical Forearm Velocity	649.63*	89.99*	0.96*
	Vertical upper arm velocity	-758.87*	151.02*	-0.63*
	Elbow Flexion Velocity	0.87*	0.16*	0.41*
	Forearm Pronation Velocity	-0.53*	0.14*	-0.24*
	Hip Flexion	-11.60*	2.77*	-0.26*
	Forearm Pronation	9.46*	2.21*	0.29*

Note: Model B1: $R^2 = 0.04$, Model B2: $\Delta R^2 = 0.13$ ($p < 0.05$), Model B3: $\Delta R^2 = 0.19$ ($p < 0.05$), Model B4: $\Delta R^2 = 0.01$ ($p = 0.11$), Model B5: $\Delta R^2 = 0.03$ ($p < 0.05$), Model B6: $\Delta R^2 = 0.06$ ($p < 0.05$). *Variable significantly contributes to the model ($p < 0.05$).

C3.2.3 - Model C – Prediction of ball spin from all kinematics

Table C20 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-32.02	97.46	
Upward racket velocity	187.59*	21.58*	0.82*
Racket inclination	-20.07*	5.17*	-0.21*
Upward racket trajectory pre-impact	-645.31*	322.74*	-0.15*
Upward forearm velocity	-99.31	83.48	-0.15
Elbow Flexion velocity	-0.22	0.14	-0.11
Forearm supination velocity	-0.14	0.11	-0.07
Upward humerus velocity	70.32	118.73	0.06
Forearm supination	1.37	1.85	0.04
Hip extension	1.07	2.32	0.03

R^2 = 0.72. *Variable significantly contributes to the model ($p < 0.05$).

C3.2.4 - Model D – Prediction of upward racket velocity from human kinematics

Table C21 – Exploratory Model

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-0.19	0.51	
Upward forearm velocity	3.27*	0.30*	1.11*
Hip extension velocity	<0.1	<0.01	-0.02
Elbow flexion	<0.01	0.01	0.01
Elbow Flexion velocity	0.01*	<0.01*	0.56*
Forearm supination velocity	<-0.01*	<0.01*	-0.24*
Upward humerus velocity	-3.68*	0.50*	-0.74*
Forearm supination	0.03*	0.01*	0.20*
Hip extension	-0.08*	0.01*	-0.41*

$R^2 = 0.65$. *Variable significantly contributes to the model ($p < 0.05$).

Table C22 – Final model omitting influential cases

Model	Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
D1	(Constant)	4.35	0.44	
	Vertical Forearm Velocity	0.59*	0.22*	0.20*
D2	(Constant)	4.53	0.40	
	Vertical Forearm Velocity	2.79*	0.42*	0.95*
	Vertical upper arm velocity	-4.46*	0.74*	-0.85*
D3	(Constant)	1.70	0.41	
	Vertical Forearm Velocity	3.81*	0.34*	1.30*
	Vertical upper arm velocity	-4.22*	0.58*	-0.81*
	Elbow Flexion Velocity	0.01*	<0.01*	0.68*
D4	(Constant)	0.53	0.42	
	Vertical Forearm Velocity	3.81*	0.31*	1.30*
	Vertical upper arm velocity	-4.50*	0.53*	-0.86*
	Elbow Flexion Velocity	0.01*	<0.01*	0.66*
	Hip Flexion	-0.06*	0.01*	-0.30*
D5	(Constant)	0.02	0.46	
	Vertical Forearm Velocity	3.53*	0.32*	1.20*
	Vertical upper arm velocity	-4.11*	0.54*	-0.79*
	Elbow Flexion Velocity	0.01*	<0.01*	0.67*
	Hip Flexion	-0.06*	0.01*	-0.33*
	Forearm Pronation Velocity	<-0.01*	<0.01*	-0.14*
D6	(Constant)	0.03	0.44	
	Vertical Forearm Velocity	3.43*	0.31*	1.17*
	Vertical upper arm velocity	-4.02*	0.52*	-0.77*
	Elbow Flexion Velocity	0.01*	<0.01*	0.59*
	Hip Flexion	-0.07*	0.01*	-0.39*
	Forearm Pronation Velocity	<-0.01*	<0.01*	-0.20*
	Forearm Pronation	0.03*	0.01*	0.21*

Note: Model D1: $R^2 = 0.04$, Model D2: $\Delta R^2 = 0.17$ ($p < 0.05$), Model D3: $\Delta R^2 = 0.31$ ($p < 0.05$), Model D4: $\Delta R^2 = 0.09$ ($p < 0.05$), Model D5: $\Delta R^2 = 0.02$ ($p < 0.05$), Model D6: $\Delta R^2 = 0.03$ ($p < 0.05$). *Variable significantly contributes to the model ($p < 0.05$).

Appendix C3.3 - Regression Models for single- and double-handed backhands

C3.3.1 - Model A – Prediction of ball spin from racket kinematics

Table C23 – Single-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-768.16	763.90	
Upward racket velocity	156.57*	19.14*	0.67*
Racket inclination	-25.03*	7.81*	-0.24*
Upward racket trajectory	3.21	5.53	0.04
Racket velocity vector	19.22	15.29	0.11

R^2 = 0.79. *Variable significantly contributes to the model ($p < 0.05$).

Table C24 – Double-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	261.92	491.72	
Upward racket velocity	139.93*	17.29*	0.60*
Upward racket trajectory	-1.49	3.66	-0.03
Racket velocity	-11.90	13.64	-0.06
Racket inclination	31.68*	8.34*	0.31*

R^2 = 0.64. *Variable significantly contributes to the model ($p < 0.05$).

C3.3.2 - Model B – Prediction of ball spin from human kinematics

Table C25 – Single-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-1445.41	298.51	
Upward forearm velocity	489.56*	109.38*	0.65*
Hip extension velocity	0.16	0.77	0.02
Elbow Flexion	1.61	4.33	0.04
Elbow Flexion velocity	-0.30	0.27	-0.12
Forearm supination velocity	1.57*	0.23*	0.79*
Upward humerus velocity	-266.55	184.79	-0.22
Forearm supination	-6.17	5.25	-0.10
Hip extension	-8.76	5.88	-0.20

$R^2 = 0.72$. *Variable significantly contributes to the model ($p < 0.05$).

Table C26 – Double-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-235.28	213.18	
Upward forearm velocity	393.51*	126.87*	0.45*
Hip extension velocity	-0.18	0.63	-0.03
Elbow Flexion	5.26	4.65	0.11
Elbow Flexion velocity	1.04*	0.36*	0.27*
Forearm supination velocity	0.15	0.25	0.05
Upward humerus velocity	-563.97*	191.43*	-0.41*
Forearm supination	8.41*	3.23*	0.25*
Hip extension	-17.85*	3.70*	-0.45*

$R^2 = 0.42$. *Variable significantly contributes to the model ($p < 0.05$).

C3.3.3 - Model C – Prediction of ball spin from all kinematics

Table C27 – Single-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	14.34	258.96	
Upward racket velocity	220.02*	69.16*	0.94*
Upward racket trajectory pre-impact	-599.01	451.94	-0.11
Upward forearm velocity	-93.30	97.87	-0.12
Forearm supination velocity	-0.20	0.24	-0.10
Racket inclination	19.29*	6.71*	0.19*
Racket angle	-9.17	12.23	-0.14

R^2 = 0.83. *Variable significantly contributes to the model ($p < 0.05$).

Table C28 – Double-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-73.79	130.78	
Upward racket velocity	145.72*	23.69*	0.64*
Upward forearm velocity	28.04	109.35	0.03
Racket inclination	23.00*	7.53*	0.24*
Elbow Flexion velocity	-0.02	0.29	<-0.00
Upward humerus velocity	-3.63	167.39	<-0.00
Forearm supination	2.43	2.43	0.07
Hip extension	1.49	3.67	0.04

R^2 = 0.62. *Variable significantly contributes to the model ($p < 0.05$).

C3.3.4 - Model D – Prediction of upward racket velocity from human kinematics

Table C29 – Single-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-5.31	0.89	
Upward forearm velocity	3.94*	0.32*	1.22*
Hip extension velocity	<0.01	<0.01	0.03
Elbow flexion	<0.01	0.01	0.01
Elbow Flexion velocity	<0.01*	<0.01*	0.13*
Forearm supination velocity	<-0.01*	<0.01*	-0.48*
Forearm supination	-0.04*	0.02*	-0.15*
Hip extension	-0.05*	0.02*	-0.26*
Upward humerus velocity	-3.18*	0.55*	-0.62*

R^2 = 0.87. *Variable significantly contributes to the model ($p < 0.05$).

Table C30 – Double-handed backhand

Variable	Unstandardised Beta Coefficient	Standard Error Unstandardised Beta	Standardised Beta Coefficient
(Constant)	-0.50	0.71	
Upward forearm velocity	2.03*	0.42*	0.54*
Hip extension velocity	<0.01	<0.01	-0.01
Elbow flexion	0.03	0.02	0.14
Elbow Flexion velocity	0.01*	<0.01*	0.38*
Forearm supination velocity	<-0.01	<0.01	-0.11
Forearm supination	0.03*	0.01*	0.18*
Hip extension	-0.10*	0.01*	-0.56*
Upward humerus velocity	-2.94*	0.64*	-0.49*

R^2 = 0.66. *Variable significantly contributes to the model ($p < 0.05$).