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Kinematic Changes of the Tennis Forehand Ground Stroke as Post Contact Ball Speed Increases

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Ball Speed Increases

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A thesis submitted to the faculty of
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ABSTRACT

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Neuromuscular and kinematic patterns during the tennis forehand have been studied extensively. However, no one has evaluated potential upper-extremity kinematic changes during the forehand as ball speed increases. The purpose of this study was to evaluate changes in shoulder and trunk kinematics as forehand ball speed increased, in an attempt to better understand how kinematics may promote forehand ball speed. Peak trunk rotation angle, shoulder horizontal abduction/adduction and internal/external rotation angle, and corresponding angular velocities were measured between initial backswing and ball contact during forehands that were performed at three different speeds (50%, 75%, and 100% of maximal post-impact ball speed). Between-speed differences were observed for all dependent variables. Internal humeral rotation velocity increased by 136% (from 477°/s to1128°/s) while trunk rotation velocity increased by 91% (from 164°/s to 313°/s) and trunk rotation angle increased by only 26% (from 46° to 58°) as forehand ball speed increased from slow to fast. Two primary conclusions can be drawn from these results: (1) trunk and upper arm rotation (adduction and internal rotation) are important to produce forehand ball speed, and (2), increased joint angular velocity may be more important than altered joint position when attempting to produce maximal forehand ball speed.

Keywords: kinematic, tennis, forehand

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Introduction

An effective forehand groundstroke is essential to successfully play tennis at any level. It is generally the first stroke taught to beginners and is a fundamental part of the game throughout a player's career. A clear understanding of the biomechanics that relate to forehand ball speed should help coaches more effectively analyze forehand performance and better teach players to perform the forehand.

The biomechanics of the forehand have been previously studied, including lower-body, upper-body, and racket kinematics (Degutis, 1966; Murphy, 1979; Groppel, 1986; Elliott *et al.*, 1987; Elliott *et al.*, 1989; Knudson, 1991; Elliott, 1995; Elliott, 1996; Bahamonde, 1999, 2001; Bahamonde & Knudson, 2003; Elliott, 2006). Muscle activation patterns have also been explored in order to better understand what muscle patterns can most effectively produce the forehand movement (Slater-Hammel, 1949; Adelsberg, 1986; Ryu *et al.*, 1988; Chow *et al.*, 1999; Knudson, 2000; Chow *et al.*, 2007). Other researchers have explained factors that affect ball spin and trajectory of the forehand stroke (Blievernicht, 1968; Elliott & Marsh, 1989; Takahashi *et al.*, 1996). Despite all of this extensive research, the biomechanics of producing greater forehand ball speed has not been explicitly studied.

Numerous factors probably contribute to increased forehand ball speed. Some of these factors are related to mechanical characteristics of the racket (e.g., racket and string composition, and racket design; Brody, 1985). Neuromuscular factors are also likely to influence forehand ball speed, including motor unit recruitment rate, number of motor units recruited, and muscle fiber length, size, and type (McBride *et al.*, 2003; Brooks, 2005; Knight & Kamen, 2008). Numerous biomechanical variables are also likely related to forehand ball speed, including lower and upper-extremity kinematics and kinetics. The focus of this study is trunk and shoulder kinematics.

As forehand ball speed increases, the trunk, shoulders, and dominant arm are expected to rotate more toward the side of the dominant arm. This facilitates increased muscle stretch and increased potential elastic energy in the musculotendon units of the trunk and upper-extremities (Elliott *et al.*, 1989). It has been suggested that humeral internal rotation is the single greatest contributor to racket head speed for topspin forehands; shoulder abduction as the second highest contributor (Takahashi *et al.*, 1996). For similar reasons, golfers increase torso and pelvis angles to increase club head speed (Myers *et al.*, 2008).

The purpose of this study is to more explicitly understand how trunk and shoulder kinematics change as tennis players hit the forehand groundstroke with increased ball speed. We asked the following research question: How do trunk and upper-extremity kinematics change as forehand ball speed increases? We hypothesized that as forehand ball speed increases, the following kinematic variables would increase (between initial backswing and ball contact): (1) peak trunk rotation angle and angular velocity, (2) peak shoulder horizontal abduction angle and adduction angular velocity (3) peak shoulder external rotation angle and internal rotation angular velocity.

Methods

Subjects

Twelve high-level male tennis players (height = 1.77 ± 0.04 m; mass = 74 ± 8 kg) participated in this study. Seven subjects were competing on a local collegiate team at the time of data collection. One subject had recently finished competing for the aforementioned team, and the others competed at a level of at least 4.5, as classified by the United States Tennis Association. Nine of the subjects were right handed. None of the subjects were injured at the time of data collection. Before data collection, informed consent that had been approved by the appropriate ethical committee was given by each subject.

Data Collection

Height and mass were measured and nine reflective markers were applied to each subject. These markers were placed over the sacrum, T10, C7, bilateral anterior superior iliac spines, bilateral acromion processes, and the medial and lateral epicondyles of the hitting elbow (Figure 1). Three reflective markers were applied to a Prince O3 Tour racket that was used by all subjects. Three-dimensional coordinate data for each marker were collected for all trials using ten high-speed video cameras (240 Hz; VICON, Santa Monica, CA, USA).

The subjects then warmed up by hitting forehands into a net until they verbally stated that they felt warmed up and comfortable with the testing environment. This warm up did not exceed five minutes, consisted of approximately 30 forehand strokes, and allowed subjects to become familiar with hitting the ball in the laboratory while wearing the reflective markers. A ball machine fed tennis balls to the subjects; this ball machine was 4.0 meters behind the net and 9.5 meters in front of subject, Figure 2). Each ball was ejected from the ball machine at a velocity of 11 m/s, bounced once on the floor, and was then struck by the subject. Subjects were instructed to aim for a marked target zone (0.6 X 0.6 m) that was 1.2 m above the floor and represented a competitive setting (Figure 2). Each struck ball was required to land in the target zone. Post-contact ball speed for all trials was measured using a radar gun (Stalker Solo 2 Radar Gun, Plano, TX, USA) that was aimed at the ball-racket contact location.

Following the warm-up forehands, five maximal-speed trials were completed in order to determine the speed all other trials would be compared to. These maximal-speed trials were considered satisfactory if the subject verbally expressed confidence that he produced a maximal effort, and hit the ball cleanly off of the racket and inside the target zone. Two submaximal ball speeds were then calculated (medium =75 ± 2.5% of max; low = 50 ± 2.5% of max). Each subject then performed five successful forehands at the three different speeds (maximal, medium, and low), in a counterbalanced order. Approximately 15-20 forehands were required to obtain five successful trials for each ball speed. All subjects were instructed to hit the same type of forehand (e.g. topspin vs. flat, open vs. closed stance) for each of the three conditions. Trials were considered successful if the ball landed inside of the target zone, and the subject and researcher subjectively determined the forehand to be good. Approximately five seconds elapsed between each forehand.

Data Analysis

Three-dimensional coordinates for each reflective marker were calculated using VICON Nexus software (VICON, Santa Monica, CA, USA). Coordinates were imported into Visual 3D software (C-Motion, Inc., Germantown, MD) in order to calculate trunk and shoulder joint angles. The pelvic coordinate system was defined using the CODA pelvis coordinate system (Collen et al., 2005). The trunk segmental coordinate system originated at the midpoint of the ASIS markers, along the negative y-axis of the pelvis (90% of the inter-ASIS distance), and along the positive z-axis (25% of the inter-ASIS distance). The long axis of the trunk was defined as a line from the origin to the midpoint of the acromion markers. The anterior-posterior axis was defined as a line that was perpendicular to the plane created by the origin, midpoint of the acromion markers, and one of the acromion markers. The medial-lateral axis was defined as the cross product of the anterior-posterior and long axes. The origin of the upper-arm coordinate system was defined as a location that was 4 cm inferior to the right acromion. The long axis was defined as a line from the origin to the midpoint of the medial and lateral epicondyles and the anterior-posterior axis was defined as an axis that was perpendicular to the plane defined by the origin and the elbow markers. The medial-lateral axis was defined as the cross product of the anterior-posterior and long axes. Trunk angle was calculated as the relative angle between the pelvis and trunk segments, while shoulder angles were calculated as relative angles between the trunk and upper-arm segments. A cardan rotation sequence of X-Y-Z was used for all joint angles. Prior to joint angle calculations, the coordinate data were smoothed using a 10 Hz low-pass Butterworth filter (Gordon & Dapena, 2006; Bonnefoy *et al.*, 2009).

Statistics

A repeated measures analysis of variance ($\alpha = 0.05$) was used to compare the effect of the independent variable (ball speed) on the dependent variables (maximal trunk rotation, humeral horizontal abduction, and humeral external rotation angles, and maximal trunk rotation, humeral horizontal adduction, and humeral internal rotation angular velocities). Sidak's *post hoc* comparisons were used to determine the specific between-speed differences detected by the repeated measures ANOVA.

Results

Means and standard deviations for each dependent variable, and corresponding graphs are presented in Table 1 and Figure 3. Ball speed significantly influenced all dependant variables. Average fast, medium, and slow ball speeds were 42.7 ± 3.8 m/s, 32.1 ± 2.9 m/s, 21.4 ± 2.0 m/s, respectively. Peak trunk angle was not significantly different between the fast and medium speeds (*p* = 0.11), but was 15% greater for the medium speed than for the slow speed (*p* < 0.001). Peak trunk rotation angular velocity was 48% greater during the fast speed than during the medium speed (*p* = 0.002), and 29% greater during the medium speed than during the slow speed (*p* < 0.001). Shoulder horizontal abduction angle for the fast speed was 19% greater than for the medium speed (*p* = 0.010). Medium and slow speeds differed by 17% for shoulder horizontal abduction angle (*p* = 0.001). Peak shoulder horizontal adduction angular velocity was 23% greater for the fast speed, compared to medium (*p* < 0.001), while medium and slow shoulder adduction angular velocities differed by 71% (*p* = 0.001). Peak shoulder internal rotation angles increased by 30% from medium to fast (*p* = 0.001), and by 22% from slow to medium (*p* < 0.001). Finally, peak shoulder internal rotation angular velocity exhibited a 43% increase from medium to fast (*p* < 0.001) and a 65% increase from slow to medium (*p* < 0.001). In summary, all of the dependent variables changed significantly as forehand ball speed increased. Joint angles appeared to change relatively less than joint angular velocities as forehand ball speed increased and changes in arm velocities were greater than changes in trunk velocities.

Discussion and Implications

The purpose of this study was to evaluate potential alterations in trunk and shoulder kinematics, associated with increases in forehand ball speed. Each observed trunk and shoulder kinematic variable changed significantly as forehand ball speed increased. The current values of peak shoulder external rotation angle, internal rotation velocity, and maximal trunk angles are comparable to previously reported values (Takahashi *et al.*, 1996). The recorded angular velocities appeared to increase disproportionately more than the peak joint angles. This may indicate that joint angular velocity is more important than joint angle to increasing forehand ball speed.

Relative to trunk and shoulder adduction/abduction, internal humeral rotation increased the most from the slow to fast ball speed. This may indicate that this variable is most important in producing increased forehand ball speed. This corroborates a previously suggested idea, that more than 40% of ball speed can be attributed to humeral internal rotation (Takahashi *et al.*, 1996). Prior to ball contact, the humerus internally rotates to increase racket speed and create the proper orientation of the racket face. The observed disproportionate increases for humeral internal rotation may likely be related to at least two factors. First, the humerus is near the end of the kinetic chain in which each body segment works together in a linked system. The legs produce kinetic energy which is then transferred to the torso and arm. As such, the humerus is the recipient of the produced kinetic energy (Groppel, 1992). Second, the humerus has a relatively small mass and moment of inertia about the long axis; these relatively small anthropometric characteristics facilitate larger rotation velocities.

Along with increased angular velocities, the data indicate that peak joint angles are also important to increased forehand ball speed. Shoulder horizontal abduction angles and trunk angles increased as post-contact ball speed increased. Other authors have observed that increased separation between the hips and shoulders allows for increased racket head speed (Groppel, 1986; Elliott & Marsh, 1989; Elliott, 1995; Takahashi *et al.*, 1996). These increased joint angles also allow for increased joint torques. Previous research has shown that the greatest resultant internal joint torque at the shoulder is produced through horizontal adduction (Bahamonde & Knudson, 2003). The size of the muscles acting on the shoulder (pectoralis major/anterior deltoid) allows for the highest horizontal adduction torque compared to other components of the movement. It can, however, be assumed that the increased maximal shoulder angle allowed for a greater maximal shoulder horizontal adduction velocity due to stretching of the muscle tissue and increased distance to accelerate the arm and ball.

In accordance with the current findings, maximal joint angles and velocities should be increased in order to increase ball speed production. Therefore, improving function of the muscles acting on the shoulder and trunk will facilitate increased trunk, arm, and ball velocities. Training specific muscles increases muscle fiber size and function for a particular muscle or group of muscles (Brooks, 2005). Resistance training should be used effectively to improve muscle size and function. Electromyography (EMG) analysis has shown that the pectoralis major, biceps brachii, subscapularis, and serratus anterior have high activity in the forward swing of a tennis forehand and should be targets of resistance training (Ryu *et al.*, 1988). Dynamic, explosive movements increase power and coordination in these involved muscles to increase the velocity of the forehand without sacrificing technique. This is explained by the disproportionate increase in joint velocity compared to joint angle (Table 1).

This study was unique in that kinematic differences were observed as forehand ball speed increased from slow to medium and fast. However, the laboratory setting did not simulate a tennis court environment and may have affected forehand performance. In the future, a similar study, conducted in a competition setting, could further our knowledge of producing forehand ball speed. Also, future research should utilize EMG to quantify neuromuscular activation patterns as forehand ball speed increases.

Conclusion

Research focusing on how to produce greater ball speed in the tennis forehand is lacking, while the topic is important to improving tennis performance. This study focused on trunk and shoulder angles and velocities as they relate to increased ball speed production. As post-contact ball speed increases, the trunk and shoulders rotate through a larger range of motion and at a higher velocity. In order to obtain greater ball velocities, a strength training routine should be implemented to focus on the specific muscles and movements performed in a tennis forehand.

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Table 1. Means and standard deviations for maximal trunk and shoulder angles and velocities for each of the three ball speeds. Changes in velocity were greater between conditions compared to changes in angle. Also, changes between conditions for the arm were greater than for the trunk. PTRA = peak trunk rotation angle, PTRAV = peak trunk rotation angular velocity, PSHAA = peak shoulder horizontal abduction angle, PSHAAV = peak shoulder horizontal adduction angular velocity, PSIRA = peak shoulder internal rotation angle, PSIRAV = peak shoulder internal rotation angular velocity. The asterisks indicate statistical significance.

	Slow	Medium	Fast	% Change (Slow/Fast)
PTRA (°)	46 ±15*	53 ± 14*	58 ± 14	26%
PTRAV (°/s)	164 ± 66*	211 ± 85*	313 ± 89*	91
PSHAA (°)	23 ± 7*	27 ± 7*	32 ± 12*	39
PSHAAV (°/s)	188 ± 47*	321 ± 59*	394 ± 80*	110
PSIRA (°)	50 ± 11*	61 ± 10*	79 ± 12*	58
PSIRAV (°/s)	477 ± 93*	789 ± 175*	1128 ± 220*	136

Table 2. Independent and Dependant Variables

Independent Variable
Ball Speed

Conditions
Fast, Medium, Slow

Dependant Variables	Assumed Hypothesis
1. Peak trunk rotation angle, from backswing to ball contact	Increase as ball speed increases
2. Peak trunk rotation angular velocity, from backswing to ball contact	Increase as ball speed increases
3. Peak shoulder horizontal abduction angle, from backswing to ball contact	Increase as ball speed increases
4. Peak shoulder horizontal adduction angular velocity, from backswing to ball contact	Increase as ball speed increases
5. Peak shoulder external rotation angle, from backswing to ball contact	Increase as ball speed increases
6. Peak shoulder internal rotation angular velocity, from backswing to ball contact	Increase as ball speed increases

Figure Legends

Figure 1. Posterior (A) and anterior (B) views of one subject with reflective markers on the hitting elbow, sacrum, T10 vertebrae, C7 vertebrae, and both acromion processes.

Figure 2. The view of the experimental set-up from the perspective of the subjects. Notice the ball machine that ejected tennis balls through the hole in the net toward the subjects. The subjects then returned each ejected ball toward the ball machine and net.

Figure 3. Means and standard errors of forehands hit at three different speeds (slow, medium, and maximal) for maximal (A) trunk rotation angle, (B) trunk rotation angular velocity, (C) shoulder horizontal abduction angle, (D) shoulder horizontal adduction angular velocity, (E) shoulder external rotation angle, and (F) shoulder internal rotation angular velocity (all variables measured from initial backswing to ball contact). The asterisks indicate statistical significance.

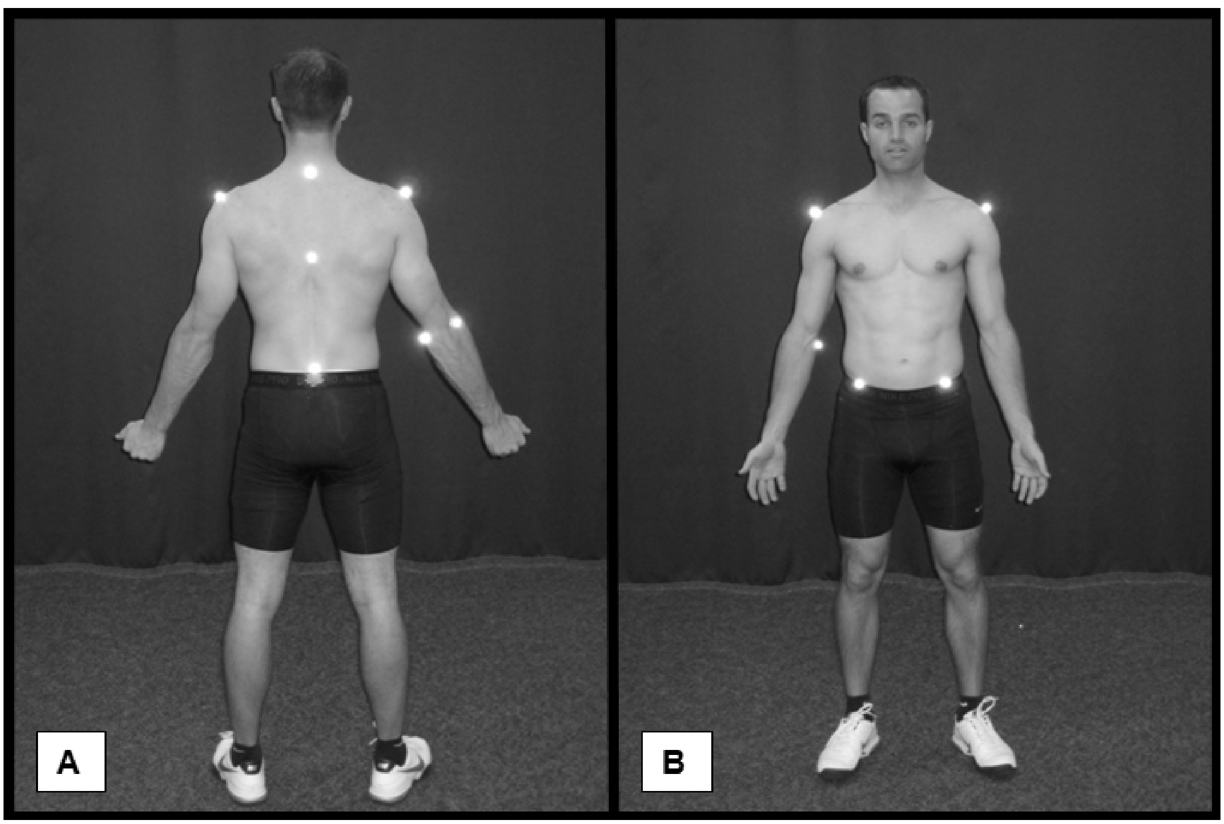


Figure 1

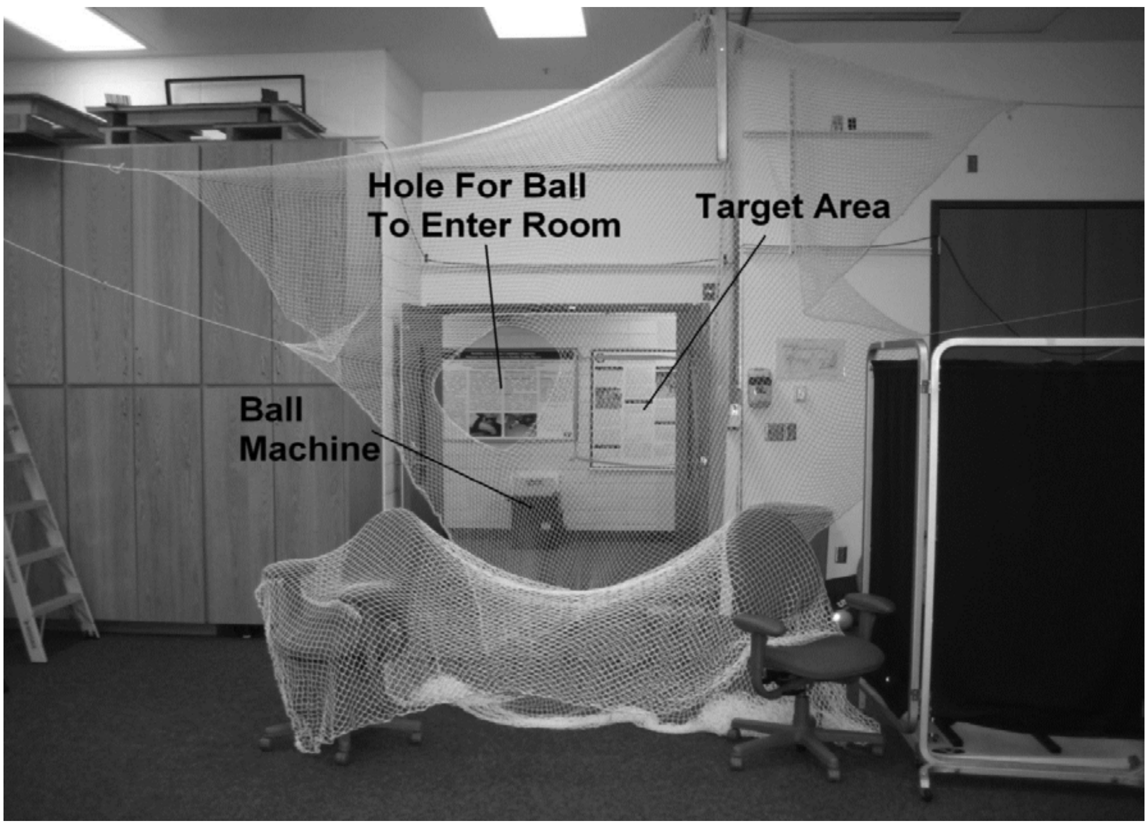


Figure 2

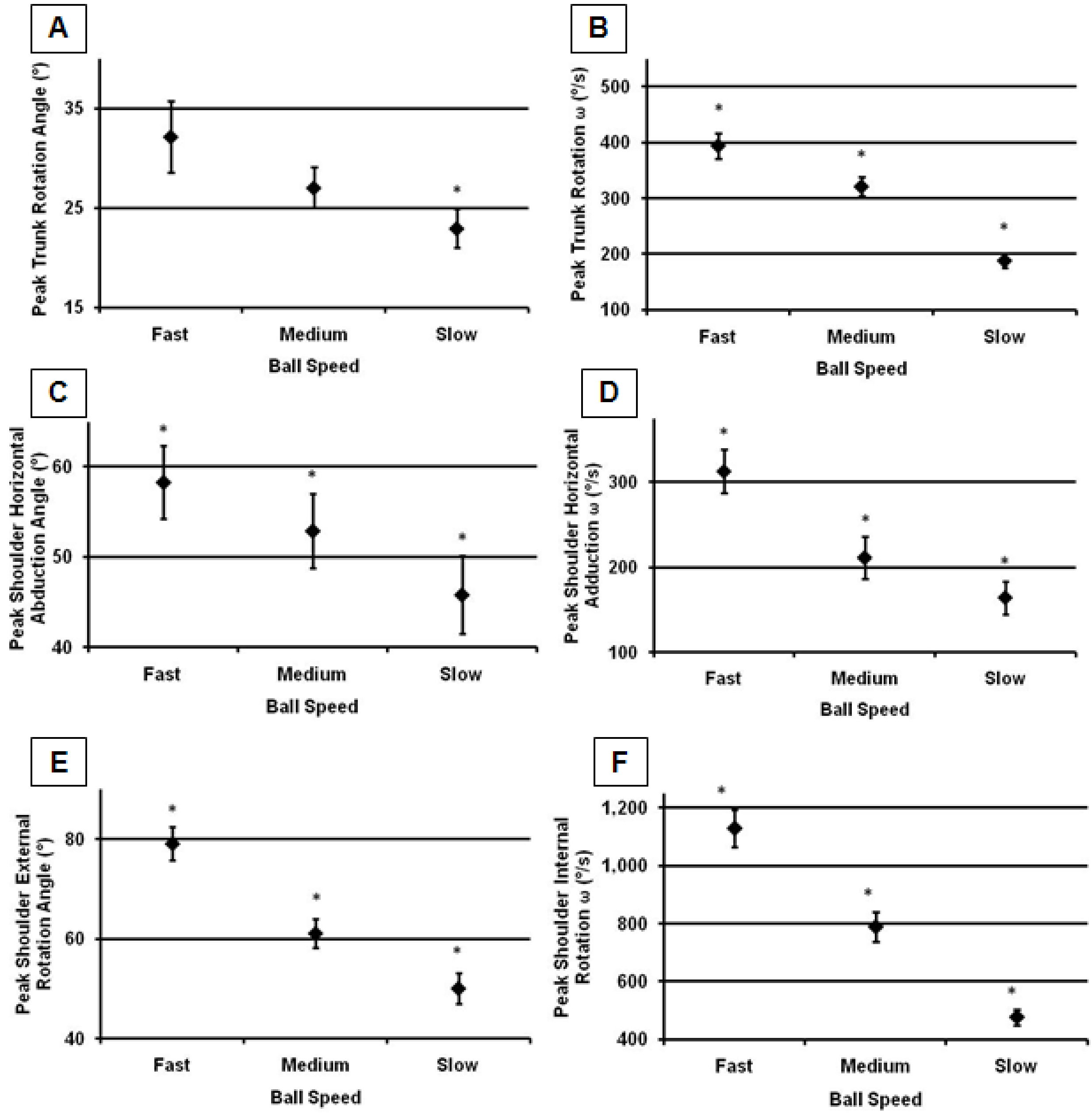

A
Peak Trunk Rotation Angle (°)
35
25
15
*
Fast
Medium
Slow
Ball Speed
B
Peak Trunk Rotation ω (°/s)
500
400
300
200
100
*
Fast
Medium
Slow
Ball Speed
C
Peak Shoulder Horizontal Abduction Angle (°)
60
50
40
*
Fast
Medium
Slow
Ball Speed
D
Peak Shoulder Horizontal Adduction ω (°/s)
300
200
100
*
Fast
Medium
Slow
Ball Speed
E
Peak Shoulder External Rotation Angle (°)
80
60
40
*
Fast
Medium
Slow
Ball Speed
F
Peak Shoulder Internal Rotation ω (°/s)
1,200
1,000
800
600
400
*
Fast
Medium
Slow
Ball Speed

Figure 3

Appendix A

Prospectus

Chapter 1

Introduction

An effective forehand groundstroke is essential to successfully play tennis at any level. It is generally the first stroke taught to beginners and is a fundamental part of the game throughout a player's career. A clear understanding of the biomechanics involved in producing ball speed during the forehand should help coaches more effectively analyze performance of the stroke and give players an increased ability to utilize the stroke. The tennis forehand has been extensively analyzed with respect to kinematics (R. Bahamonde, 1999, 2001; R. E. Bahamonde & Knudson, 2003; Degutis, 1966; B. Elliott, 1996, 2006a; B. Elliott, Marsh, & Overh, 1987; B. Elliott, Marsh, & Overheu, 1989; B. C. Elliott, 1995; Groppel, 1986; Knudson, 1991; Murphy, 1979), muscle activation patterns (Adelsberg, 1986; J. W. Chow, et al., 1999; John W. Chow, Knudson, Tillman, & Andrew, 2007; Knudson, 2000; Ryu, McCormick, Jobe, Moynes, & Antonelli, 1988; Slater-Hammel, 1949), and ball spin and trajectory (Blievernicht, 1968; B. Elliott & Marsh, 1989; Takahashi, Elliott, & Noffal, 1996); however, the relationship between these variables and forehand ball speed is unclear.

Numerous factors are likely to contribute to increased forehand ball speed. Some of these factors are related to the mechanical characteristics of the tennis racket such as racket and string composition, and racket design (Brody, 1985). Other factors that are likely to affect forehand ball speed are neuromuscular in nature. Some of these potential neuromuscular factors include the electrical activity of the muscle, rate of motor unit recruitment, number of motor units recruited, and muscle fiber length, size, and type (Brooks, 2005; Knight & Kamen, 2008; McBride, Blaak, & Triplett-McBride, 2003). These likely neuromuscular factors influence the biomechanics of the forehand. However, this study will focus on several key biomechanical measures that are potentially related to tennis forehand ball speed.

Biomechanical variables are likely related to increased forehand ball speed. As forehand ball speed increases, the trunk, shoulders, and dominant arm are expected to rotate more toward the side of the dominant arm (B. Elliott, et al., 1989). Theoretically, this increased rotation results in increased potential elastic energy that is stored in the musculotendon units of the trunk and upper-extremities. This increased rotation also results in increased time and displacement for tennis players to produce racket head speed. A similar strategy is used by golfers who wish to increase club head speed (Myers, et al., 2008). The purpose of this study is to better understand how these specific potential biomechanical changes affect forehand ball speed.

We formulated the following research question, related to the purpose of our study: How are trunk and upper-extremity mechanics altered in order to produce increased forehand ball speed? Related to this research question, we articulated several hypotheses. We hypothesized that as forehand ball speed increases, the following biomechanical variables will increase: (1) peak trunk rotation angle, between initial backswing to ball contact, (2) peak trunk rotation angular velocity, between initial backswing to ball contact, (3) peak shoulder horizontal abduction angle, between initial backswing to ball contact, and (4) peak shoulder horizontal abduction angular velocity, between initial backswing to ball contact.

Statement of Purpose

The purpose of this study is to better understand how trunk and shoulder mechanics change with increases in forehand ball speed.

Hypothesis

As forehand ball speed increases, the following biomechanical variables will increase: (1) peak trunk rotation angle, between initial backswing to ball contact, (2) peak trunk rotation angular velocity, between initial backswing to ball contact, (3) peak shoulder horizontal abduction angle, between initial backswing to ball contact, and (4) peak shoulder horizontal abduction angular velocity, between initial backswing to ball contact (see Table 1).

Assumptions

1. Participants will be representative of current high level, male tennis players throughout the world.
2. Participants will perform forehand strokes as they normally would in a competition.
3. All laboratory equipment will be calibrated correctly.
4. Participants will be healthy.
5. Participants must be able to complete the total number of forehand strokes under each test condition.

Delimitations

1. Participants will be on the current university tennis team or rated at least 4.5 by the USTA.

Limitations

The biomechanical changes observed will only be applicable to tennis players competing on the university tennis team or that are rated 4.5 or higher by the USTA.

Definition of Terms

Closed Stance – A stance where the forward foot and back foot are perpendicular to the net.

Forehand – Tennis groundstroke performed on the same side of body as the dominant arm.

Open Stance – A stance where the feet are aligned parallel to the net.

Shoulder Horizontal Angle – Angle between the front plane of the body and the upper arm in the transverse plane.

Shoulder Horizontal Angular Velocity – Change in angle between the arm and front of the body in the transverse plane over a certain period of time.

Trunk Rotation Angle – Angle between the hips and shoulders.

Trunk Rotation Angular Velocity – Change in angle between the hips and shoulders over a certain period of time.

USTA – United States Tennis Association

Multi-segment Forehand – A stroke where a player turns the shoulders and then rotates the racket around the elbow to hit the ball.

Single Unit Forehand – A stroke where a player turns the shoulders and extends the elbow simultaneously and swings them forward as one unit.

Chapter 2

Review of Literature

Introduction

The mechanics of successful athletes are often studied to gain knowledge regarding the techniques that are most effective for a certain sport. The study of sport biomechanics often allows for an improved understanding of successful technique (B. Elliott, 2006b). There is always a need for teachers and coaches who understand the mechanics of each stroke and know how to teach them effectively. When the fundamentals of good technique are taught and understood, players may adapt them to their own ability and style to improve their game.

At any level of play, an effective forehand groundstroke is an essential part of tennis. The forehand is usually the first stroke learned and is a cornerstone throughout a player's development. The kinematics (R. Bahamonde, 1999, 2001; R. E. Bahamonde & Knudson, 2003; Degutis, 1966; B. Elliott, 1996, 2006a; B. Elliott, et al., 1987; B. Elliott, et al., 1989; B. C. Elliott, 1995; Groppel, 1986; Knudson, 1991; Mester, Yue, & Kleinoeder, 2006; Murphy, 1979), muscle activation patterns (Ryu, et al., 1988; Slater-Hammel, 1949), and spin and direction of the ball (Blievernicht, 1968; B. Elliott & Marsh, 1989; Takahashi, et al., 1996) that are involved during the successful completion of a tennis forehand have been previously studied in detail. This research has provided an understanding of how the body should move to produce an effective forehand with or without spin. Little is known, however, regarding how the aforementioned kinematics may be altered in order to increase or decrease power in the forehand tennis stroke. This review will first summarize previously-conducted research involving lower extremity kinematics. Next, trunk kinematics will be reviewed. Third, upper extremity kinematics will be discussed. Fourth, racket head trajectory and orientation will be discussed. Finally, this review will also discuss the ball contact point, ball velocity, muscle EMG, and other variables that affect ball speed in the tennis forehand.

Lower Extremity Kinematics

The legs and feet provide the foundation for all movements on the tennis court. Proper form develops from the ground up. Energy is transferred from the ground though the legs to the torso, arm, hand, and racket to the ball. Power is produced through the summation of the movements performed by each body segment (Mester, et al., 2006). The greater the force that each individual body part contributes, the greater the sum of the forces will be if the movement is performed correctly.

Getting low to the ground provides a stable foundation for movement and, to a certain point, may allow for greater power production by allowing the leg muscles to store more elastic energy to transfer to the rest of the body parts involved in a movement. Two different types of tennis players, those who use a multi-segment forehand and those who use a single unit forehand have been studied previously with regard to their lower body movement. In preparation for a forehand stroke, both groups bent at the knees and hips to move toward the ground at about the same rate (0.52 m/s for multi-segment, and 0.49 m/s for single unit). They then decelerated to put the lower extremity muscles on stretch (B. Elliott, et al., 1989). An increase in time between stretching and shortening a muscle leads to a decrease in the amount of energy stored, with half of the stored energy dissipating every 0.85 seconds (Wilson, Elliott, & Wood, 1991). It is therefore beneficial to have a short time between stretching and contracting a muscle. Also, as the velocity of the movement increases, the amount of stored elastic energy increases (Rack & Westbury, 1974). It is important to quickly contract the hip and leg muscles as soon as they are stretched in order to obtain the most stored elastic energy to transfer to the upper body. Therefore, by using the legs effectively, power production can be increased.

Trunk Kinematics

The energy produced and stored by the legs is transferred to the hips and trunk. In preparation for a tennis forehand stroke, the hips and trunk rotate toward the dominant side of the body, stretching the abdominal muscles (rectus abdominis and internal/external obliques). Later, these stretched muscles will shorten, allowing the body to uncoil and transfer the stored energy to the arm and tennis ball (Gensemer, 1994). The rectus abdominis connects the lower and upper body movements to allow for a smooth transfer of energy (Mester, et al., 2006). The rotation of the upper body allows for increased arm speed and therefore increased ball speed (R. Bahamonde, Knudson, D, 1998; Groppel, 1986).

Upper Extremity Kinematics

Rotational motion is produced as the leg on the dominant side of the body pushes off the ground and transfers linear motion into rotational motion through the hips and trunk. The hips and trunk turn through the forehand stoke from facing the sideline to face the net. This rotational motion turns the dominant arm from a position behind the body around toward the front of it to allow increased arm extension into the hitting zone. This increases the forward movement of the arm into the ball. The hips and trunk seem to contribute more to power production than the upper limb due to the size of the muscles involved ("The Biomechanics of Tennis: An Overview," 1986).

Hip and trunk rotation also allows for greater pre-stretching of the shoulder muscles (R. Bahamonde, 2001). The shoulder is horizontally abducted in the preparation phase of the forehand to allow for the arm and racket to be accelerated in the forward direction to further increase ball velocity. Increased horizontal abduction of the shoulder may allow for more elastic energy to be stored in the muscle tissue to allow for increased power production.

The shoulders, arm, and hand are the next links in the kinetic chain. High performance tennis players rotate the shoulders approximately 0.17 radians past a line drawn perpendicular to the back fence during the backswing of a multi-segment forehand stroke and then end with the shoulders almost parallel to the net at ball impact (B. Elliott, et al., 1989; Takahashi, et al., 1996). In the modern forehand stroke, the upper arm, forearm, and wrist segments move as separate units to increase power (B. Elliott, et al., 1989). The elbow flexes during ball contact and follow through of the forehand and the wrist remains firm, but may slightly flex to increase racket velocity (B. C. Elliott, 1995).

The shoulder alignment of players who use a multi-segment or single unit forehand had similar angles at completion of the backswing (1.78 radians behind a line parallel to the net for multi-segment and 1.73 radians behind a line parallel to the net for single unit). At ball contact, shoulder angles for both groups were 0.12 radians and 0.15 radians behind a line parallel to the net for the multi-segment and single unit groups respectively. Shoulder angles were similar, but players who used the multi-segment forehand had the upper arm closer to the body at completion of the backswing (0.80 radians abducted away from body). Players who used the single unit forehand had the upper arm farther away from the body at the completion of the backswing (1.19 radians abducted away from the body). The wrists of both groups were hyper-extended to a similar extent at the completion of the backswing (multi-segment = 2.56 radians, single unit = 2.63 radians) (B. Elliott, et al., 1989).

Racket Head Trajectory

Other factors also play a part in power production for a tennis forehand. Racket head trajectory is one variable that plays an important role in the topspin forehand. As players go from a flat forehand to a topspin forehand and topspin lob the racket head trajectory becomes more vertical. Racket head trajectory was measured for each stroke as follows: pre-impact trajectories, relative to the ground, were 0.37 radians, 0.64 radians, and 0.91 radians for the flat forehand, topspin forehand, and topspin lob respectively and increased to 0.65 radians, 0.91 radians, and 1.27 radians respectively, after impact. Racket head speed decreased significantly from 16.8 m/s to 13.9 m/s and 8.7 m/s in the horizontal direction for flat, topspin, and topspin lobs respectively, and increased in the vertical direction from 7.9 m/s to 11.9 m/s and 13.3 m/s respectively (Takahashi, et al., 1996). A flatter swing will produce greater horizontal racket head velocity and increased ball speed while increased vertical racket head velocity will increase ball spin.

Racket head trajectories in forehand topspin approach shots have also been studied. Racket trajectories prior to impact followed an upward path of 0.48 radians (B. Elliott & Marsh, 1989). Similar trajectories were measured for multi-segment and single unit forehands as tennis players imparted topspin to the ball. The multi-segment group swung at 0.3 radians upward, with respect to the court, prior to ball impact and 0.83 radians upward after ball contact. The single unit group showed similar results with an angle of 0.29 radians upward prior to ball contact and 0.81 radians following ball contact (B. Elliott, et al., 1989).

Racket Head Orientation

The angle of the racket head at ball contact is another factor that affects the velocity of the tennis ball after ball contact. Racket head angles were similar for both the single unit and multi-segment forehand strokes at 0.14 radians behind a line parallel to the net (B. Elliott & Marsh, 1989). If a racket strikes the tennis ball while it is perpendicular to the ground then the spin imparted to the ball will depend on the trajectory of the racket. Topspin and backspin are produced by increasing the vertical trajectory of the racket compared to a horizontal trajectory which influences ball speed.

Forehand strokes aimed toward the right corner of the tennis court versus the left corner of the tennis court have also been analyzed. As subjects hit the ball to the left corner, racket angles were angled forward between 0.1 and 0.06 radians while the angle was between 0.07 and 0.02 radians behind a line perpendicular to the net for shots to the right corner (Blievernicht, 1968). Regardless of the type of forehand (multi-segment or single unit), players contact the tennis ball with a slightly closed or vertical racket face (0.02 to 0.12 radians forward toward the net from a line parallel to the net) (B. Elliott, et al., 1989). When comparing flat, topspin, and topspin lob forehands similar results have been reported(Takahashi, et al., 1996). The racket face was almost perpendicular to the ground at impact for the topspin lob (1.56 radians) while the top of the racket was angled slightly toward the net for the flat forehand (0.06 radians forward) and topspin forehand (0.09 radians forward). This suggests that the racket face in all forehand strokes is generally perpendicular to the ground.

Ball Contact

Ball contact point may have a correlation with the direction that the ball is hit for tennis players. They may contact the ball even with or in front of their body depending on the type of shot they are hitting. Tennis players generally have a ball contact point even with or slightly in front of their front foot when they hit the ball to the left corner of the tennis court and a contact point about 21.5 cm behind the front foot when subjects hit to the right corner (Blievernicht, 1968). This suggests that subjects hit the ball farther in front of them when they hit across their body compared to hitting shots down the same side of the court. Similar results were found in another study with subjects hitting shots to the left corner of the tennis court 17cm in front of the front foot compared to shots hit to the right corner (B. Elliott, et al., 1989).

When comparing topspin versus backspin trials, ball was contact was made significantly farther in front of the forward ankle for topspin compared to backspin trials (26 cm vs. 5 cm, respectively) (B. Elliott & Marsh, 1989). These results may suggest that the different amounts of spin are most easily achieved by hitting the ball more or less in front of you.

Ball Velocity

All of the previously described body movements have the potential to contribute to the speed of the arm and racket which translates into ball speed or spin. To produce the greatest ball speed, players used a looped backswing compared to a straight backswing (B. Elliott, et al., 1989). Maximal racket velocities were greatest prior to impact and were significantly greater in topspin trials (26.5 m/s) compared to backspin trials (16.6 m/s) (B. Elliott & Marsh, 1989).

The stance and type of forehand shot will also change the horizontal velocity of the tennis ball. Greater racket velocities at impact were achieved using the square stance compared to the open stance (22.3 and 16.4 m/s; 21.2 and 15.8 m/s) for professionals and intermediate tennis players respectively (R. E. Bahamonde & Knudson, 2003). Mean linear racket head velocities decrease as subjects progress from a flat forehand to a topspin forehand and topspin lob (16.8 m/s, 13.9 m/s, 8.7 m/s respectively), while vertical velocity increases across the three strokes (7.9 m/s, 11.9 m/s, and 13.3 m/s respectively). The increased vertical velocity created the desired topspin at the sacrifice of horizontal ball velocity (Takahashi, et al., 1996).

Electromyography (EMG)

Researchers have also described muscle activation patterns during a tennis forehand. The pectoralis major, anterior deltoid, and biceps brachii are major contributors to racket speed while the latissimus dorsi and middle deltoid act as synergists (Slater-Hammel, 1949). The more skilled a player becomes, the more consistent the timing and force of muscular contractions will be for each stroke (Groppel, 1986).

EMG has been used to describe the forehand tennis motion in an attempt to assist in injury prevention and rehabilitation (Ryu, et al., 1988). They used six uninjured Division II collegiate tennis players as subjects. EMG activity showed that during the backswing stage of a forehand, all of the muscles measured showed minimal levels of activation. In the acceleration stage the biceps brachii, subscapularis, pectoralis major, and serratus anterior all had high levels of activity. In the follow through, the biceps brachii, subscapularis, and serratus anterior muscles decreased in activity to a moderate level while the pectoralis major decreased to a low activity level. The supraspinatus, middle deltoid, and latissimus dorsi exhibited low levels of activity for all three stages of the forehand stroke.

Muscle activation and force production has also been studied in the tennis forehand (R. Bahamonde, 1999). It is known that human muscle can produce more force under an eccentric contraction compared to a concentric contraction. It is therefore advantageous to have a short time between the eccentric motion of a backswing and the concentric contraction. This promotes the most storage of energy in the elastic tissue in the muscle. A greater velocity of the contraction will produce a greater amount of stored elastic energy (R. Bahamonde, 1999; Rack & Westbury, 1974).

Other variables

Several other variables are involved in ball speed production in modern tennis. String composition, string tension, and racket design also play important roles in producing power in a tennis forehand (Brody H, 2002). Racket and string components as well as racket design can affect how much energy will be transferred to the tennis ball. Racket technology has been a means of increasing power production, but is not analyzed in this paper.

Conclusions

In summary, producing an accurate and powerful forehand is essential to effective tennis performance. Researchers have studied the forehand of many successful tennis players and general observations have been made about the most effective technique. Tennis racket and string technology has a significant effect on ball speed along with racket head orientation and trajectory. Lower extremity, trunk, and upper extremity kinematics control how the racket moves and are therefore the foundation for a more effective forehand stroke. Understanding how to incorporate the trunk and arm muscles into producing more power will allow for a more effective forehand. All of these variables have been previously analyzed, but not with respect to how they change as more power is produced.

Chapter 3

Methods

Subjects

Twelve high-level male tennis players will be recruited to participate in this study. A statement of IRB approval and a signed informed consent will be required. “High level” will be defined as either competing on the local university team, or be rated at least 4.5 by the USTA.

Data Collection

Height and mass will be measured and then 9 retroreflective markers will be applied to the subject. Single markers will be placed on the sacrum, the T10 vertebrae, and the C7 vertebrae. A single marker will also be placed on each anterior superior iliac spine and on each acromion process. Single markers will then be placed on the medial and lateral epicondyles of the hitting elbow. Three reflective markers will also be placed on the tennis racket; the same racket will be used by all subjects during all trials. The marker placement locations and corresponding anatomical coordinate systems are depicted in Figures 1-3.

After reflective markers are applied, the subjects will warm up by hitting forehands into a net (similar to testing procedure) until they verbally state that they feel warmed up and are comfortable with the testing environment. The warm up will not exceed five minutes. This will allow subjects to become familiar with hitting the ball in the laboratory while wearing the reflective markers. A ball machine will be used to feed tennis balls to the subjects. The location of this ball machine will remain the same for all subjects (ball machine = 13 feet behind net, net = 18 feet in front of subject). During the warm-up, subjects will be allowed to move to hit the ball where they feel comfortable. Each fed ball will be ejected from the ball machine, bounce once on the floor, and then be struck by the subject. Subjects will aim for a marked target zone (24 X 24 inches, 4 feet above the floor) that is set up to represent a competitive setting. Each ball is required to land in the target zone to be considered successful. Ball speed for all trials will be measured using a radar gun (Model 3400, Sports Radar, Homosassa, FL, USA). The accuracy of the radar gun was assessed using a calibration equation created using five tennis ball speeds recorded with the radar gun and verified using VICON motion analysis software. The experimental setup is depicted in Figures 4-5.

Following the warm-up forehands, subjects will be instructed to hit the ball with maximal effort to produce a standard with which to gauge the percent exertion of each subsequent maximal and sub-maximal forehand stroke in the testing protocol. These maximal-speed trials will be considered satisfactory if the subject: verbally expresses confidence that he produced a maximal effort, hit the ball cleanly off of the racket, and hit the ball inside the target zone. Additional attempts will be required until five successful maximal-speed trials are completed. Average ball speed across the five trials will be considered maximal ball speed.

Once maximal speed is determined, two submaximal ball speeds will be calculated: medium (75% of max) and low (50% of max). Each subject will then perform five successful forehands at the three different speeds (maximal, medium, and low), in a counterbalanced order.

Trials will be considered successful if the subject hits the ball at a speed within ±2.5% of the predetermined speed, the ball lands inside of the target zone, and the subject and researcher subjectively determined the forehand to be good. Approximately five seconds will elapse between each forehand. This time will be necessary to determine whether the appropriate ball speed had resulted and for the subject to reassume the hitting position. Ball speed for every trial will be determined with the aforementioned radar gun, aimed at the ball/racket contact point.

Three-dimensional coordinate data for each marker will be collected for all trials using eight high-speed video cameras (240 Hz; VICON, Santa Monica, CA, USA).

Data Analysis

Three-dimensional coordinates will be measured using VICON Nexus (VICON, Santa Monica, CA, USA). These coordinates will be imported into Matlab, and then a custom written algorithm will be used to determine: 1) peak trunk rotation angle, from backswing to ball contact, (2) peak trunk rotation angular velocity, from backswing to ball contact, (3) peak shoulder horizontal abduction angle, from backswing to ball contact, and (4) peak shoulder horizontal abduction angular velocity. Each of these variables will be averaged over the five satisfactory trials for each subject for each observed ball speed (see Table 1).

Statistics

A Repeated Measures ANOVA ($\alpha = 0.05$) will be used to compare the dependent variables across the three conditions: maximal, medium, and low. The independent variable is ball speed which consists of three conditions: maximal, medium, and low. The dependent variables are: (1) peak trunk rotation angle, from backswing to ball contact, (2) peak trunk rotation angular velocity, from backswing to ball contact, (3) peak shoulder horizontal abduction angle, from backswing to ball contact, and (4) peak shoulder horizontal abduction angular velocity. Tukey's *post hoc* comparisons will be used to determine the specific nature of any between-condition differences detected by the repeated measures ANOVA.

Table 1: Independent and Dependant Variables

Independent Variable
Ball Speed

Conditions
Fast, Medium, Slow

Dependant Variables	Assumed Hypothesis
1. peak trunk rotation angle, from backswing to ball contact	Increase as ball speed increases
2. peak trunk rotation angular velocity, from backswing to ball contact	Increase as ball speed increases
3. peak shoulder horizontal abduction angle, from backswing to ball contact	Increase as ball speed increases
4. peak shoulder horizontal abduction angular velocity	Increase as ball speed increases

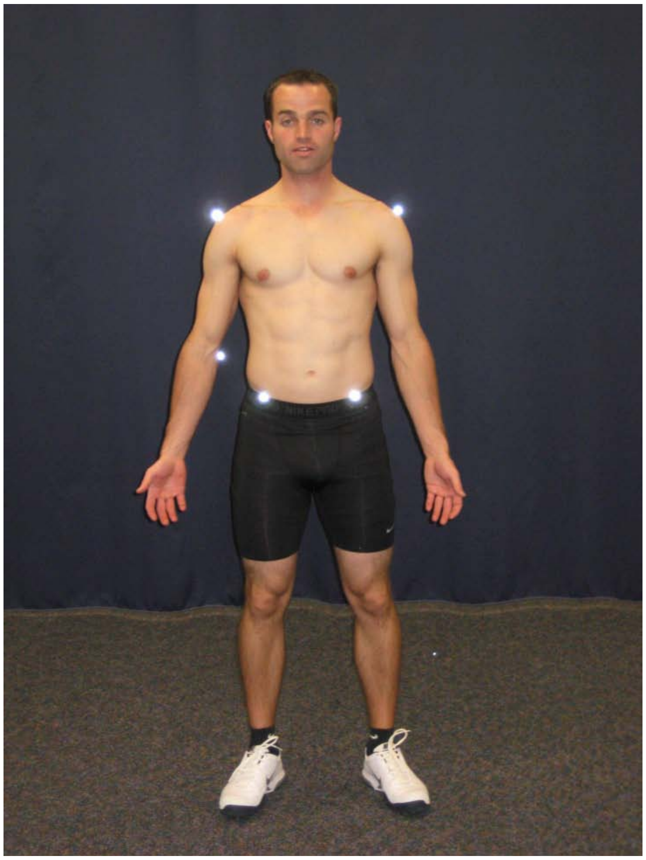
Figures

Figure 1: Posterior View

Posterior view of subject with markers on the hitting elbow,

sacrum, T10 vertebrae, C7 vertebrae, and both acromion processes

Figure 2: Anterior View



Anterior view of subject with markers on both anterior superior iliac spines, acromion processes, and the hitting elbow

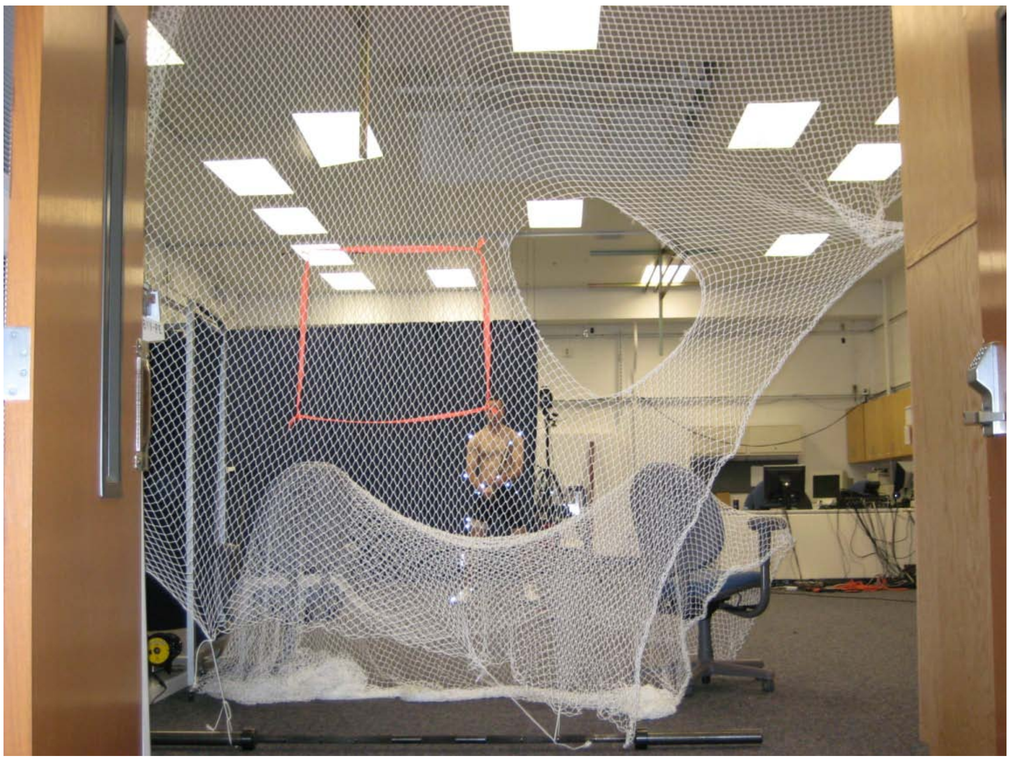
Figure 3: Tennis Racket

Tennis racket with markers on each shoulder and one on the tip

Figure 4: View from Subject

View of set-up from perspective of the subject

Figure 5: View from Ball Machine



View of set-up from the perspective of the ball machine.

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