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Research article

Influence of Tennis Racquet Kinematics on Ball Topspin Angular Velocity and Accuracy during the Forehand Groundstroke

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Abstract
Forehand groundstroke effectiveness is important for tennis success. Ball topspin angular velocity (TAV) and accuracy are important for forehand groundstroke effectiveness, and have been extensively studied, previously; despite previous, quality studies, it was unclear whether certain racquet kinematics relate to ball TAV and shot accuracy during the forehand groundstroke. This study evaluated potential relationships between (1) ball TAV and (2) forehand accuracy, and five measures of racquet kinematics: racquet head impact angle (i.e., closed or open face), horizontal and vertical racquet head velocity before impact, racquet head trajectory (resultant velocity direction, relative to horizontal) before impact, and hitting zone length (quasi-linear displacement, immediately before and after impact). Thirteen collegiate-level tennis players hit forehand groundstrokes in a biomechanics laboratory, where racquet kinematics and ball TAV were measured, and on a tennis court, to assess accuracy. Correlational statistics were used to evaluate potential relationships between racquet kinematics, and ball TAV (mixed model) and forehand accuracy (between-subjects model; $\alpha = 0.05$). We observed an average (1) racquet head impact angle, (2) racquet head trajectory before impact, relative to horizontal, (3) racquet head horizontal velocity before impact, (4) racquet head vertical velocity before impact, and (5) hitting zone length of 80.4 ± 3.6˚, 18.6 ± 4.3˚, 15.4 ± 1.4 $m \cdot s^{-1}$, 6.6 ± 2.2 $m \cdot s^{-1}$, and 79.8 ± 8.6 mm, respectively; and an average ball TAV of 969 ± 375 revolutions per minute. Only racquet head impact angle and racquet head vertical velocity, before impact, significantly correlated with ball TAV ($p < 0.01$). None of the observed racquet kinematics significantly correlated to the measures of forehand accuracy. These results confirmed mechanical logic and indicate that increased ball TAV is associated with a more closed racquet head impact angle (ranging from 70 to 85˚, relative to the ground) and increased racquet head vertical velocity before impact.

Key words: Athletic performance, sports, recreation.

Introduction

The forehand groundstroke is critical to tennis success (Johnson and McHugh, 2006; Reid et al., 2013) because it is the most frequently played stroke in tennis (Johnson and McHugh, 2006) and significantly influences match outcome. Within the competitive tennis community, it is common knowledge that points are often won or lost with strong and consistent forehand groundstrokes. Consequently, researchers have studied biomechanical characteristics of the forehand groundstroke, and numerous biomechanical factors have been found to be related to effective forehand groundstrokes (Knudson and Elliott, 2004; Knudson, 2006). For example, post-impact ball linear velocity influences forehand groundstroke effectiveness (Vergauwen et al., 2004), and trunk rotation, upper arm internal rotation, and racquet head velocity influence post-impact ball velocity for the forehand ground stroke (Elliott et al., 1989; 1997; 2009; Seeley et al., 2011). Numerous studies have been conducted concerning factors that are thought to influence linear velocity of the ball during the forehand ground stroke, however, less research has been conducted concerning factors that influence shot accuracy. Ball topspin angular velocity (TAV) is also known to influence forehand groundstroke outcome; in addition to racquet kinematics, racquet string composition and longer ball contact time (with the racquet) are known to increase ball TAV (Allen et al., 2010; 2016; Kawazoe and Okimoto, 2009). There are few quantitative data describing relationships between racquet kinematics and ball TAV, and the relationship between forehand accuracy and ball TAV has not been studied.

Researchers have established that racquet trajectory and orientation influences forehand groundstroke effectiveness, including ball TAV and shot accuracy. Racquet kinematics during successful and unsuccessful shots have been studied extensively (Knudson and Blackwell, 2005). Further, observational studies have explored relationships between forehand accuracy and various other factors including shot precision, net clearance and court depth (Davey et al., 2002; Knudson and Blackwell, 2005; Rossi et al., 2015).

One important kinematic variable that has been studied, in the context of forehand groundstroke effectiveness, is racquet head impact angle, which is a measure of how closed or open the racquet face is at the time of impact (Figure 1A; Brody, 1985; 2006; Choppin et al., 2011; Cross, 2003; Elliott et al., 1989; Knudson and Elliott, 2004; Takahashi et al., 1996). Although racquet head impact angle (Figure 1A) has been studied quite extensively, the exact strength and nature of the relationship between racquet head impact angle and ball TAV, during the forehand groundstroke, in still unclear. Choppin et al. (2011) reported that, for high-level male and female players, racquet head impact angle ranged from 14 to 33 degrees, with a mean of 21 degrees, however, racquet head impact angle during both successful and unsuccessful strokes has also been reported to be near 90˚ (Elliott et al., 1989; Knudson and Elliott, 2004); for these studies, greater angles indicated racquet faces that were more closed. Additionally, unsuccessful strokes have been associated with greater

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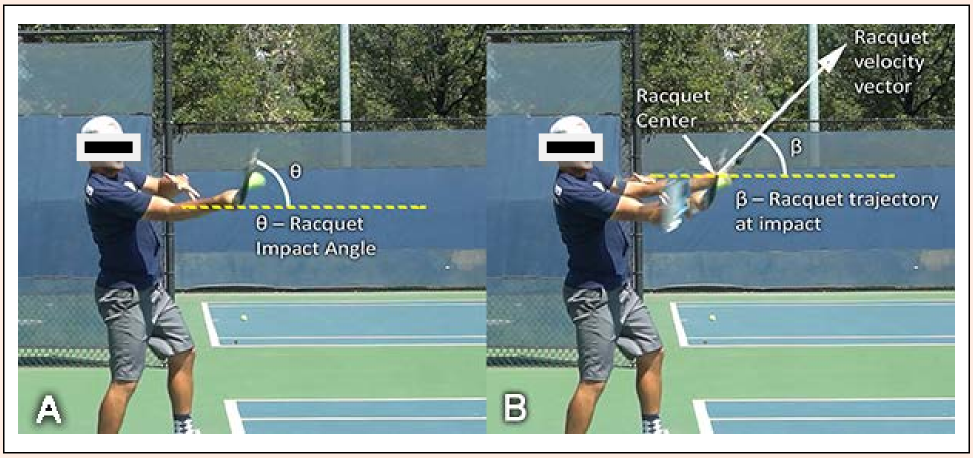

Figure 1A. A depiction of how racquet head impact angle (i.e., open or closed racquet face) was calculated, relative to a fixed horizontal axis. B. A depiction of how racquet head trajectory before impact was calculated, relative to a fixed horizontal axis.

variability in racquet head impact angle (Knudson and Blackwell, 2005), and it has been reported that there is little difference in racquet head impact angle between differing levels of tennis players (Knudson and Bahamonde, 1999; Knudson and Blackwell, 2005; Knudson, 2000; Landlinger et al., 2010). Another study of topspin approach forehands reported that the racquet face was closed approximately 7 degrees (Elliot and Marsh, 1989). Additional research might help elucidate the optimal racquet head impact angle during the forehand groundstroke, concerning the production of ball TAV and shot accuracy.

Increasing vertical velocity of the racquet head, near impact, also likely improves forehand groundstroke effectiveness (Takahashi et al., 1996); however, racquet trajectory, in the vertical plane, varies among different levels of players and different stroke types (Reid et al., 2013). Typically, advanced players hit forehand strokes with steeper racquet trajectories at impact than do novice and intermediate players, because a flatter trajectory decreases ball TAV and margin for error (Blackwell and Knudson, 2005; Groppel et al., 1983; Knudson and Blackwell, 2005). Knudson and Blackwell (2005) documented relationships between a player's ability to hit a topspin forehand without error, and racquet and ball trajectory at impact. No one, however, has evaluated the potential relationship between (1) racquet trajectory, before impact (Figure 1B), and (2) forehand groundstroke accuracy, measured as the ability to hit the forehand to the correct depth and left-to-right position on the tennis court. Although the theoretical relationship between ball TAV and shot accuracy (i.e., obtaining the desired depth of a forehand groundstroke) has been previously discussed (Blackwell and Knudson, 2005), experimental data would help explain the actual relationship between ball TAV and shot accuracy, during the forehand groundstroke.

Another characteristic that supposedly contributes to effective forehand groundstrokes is the concept of a longer (increased displacement) hitting zone, or flattened arc swing. In this context, the hitting zone refers to a quasi-straight-line distance (linear translation) over which the racquet travels, in the direction that the ball is intended to travel, immediately before and after ball impact. Anecdotally, some tennis coaches have suggested that a longer hitting zone can increase forehand accuracy (Chafin and Moore, 1994). While this idea has been presented in skill instruction and coaching literature (Chafin and Moore, 1994; Gensemer, 1985; 1994), the hitting zone concept has received little attention in the research literature.

The purpose of this study was to confirm relationships between (1) five measures of racquet kinematics, near impact, during the forehand groundstroke (hitting zone length, racquet head impact angle, racquet trajectory before impact (relative to horizontal), and racquet horizontal and vertical velocity before impact) and (2) two response variables (forehand groundstroke accuracy and ball TAV). We hypothesized that an increased hitting zone length, optimal racquet head impact angle (near 90˚) and increased vertical velocity of the racquet head would be associated with increased forehand groundstroke accuracy and ball TAV during the forehand groundstroke. This study was conducted in order to add to existing knowledge of racquet kinematics, near impact, and ball TAV and shot accuracy, during the forehand groundstroke.

Methods

Thirteen NCAA Division I, male, tennis players (Age = 20 ± 3 years; Height = 1.85 ± 0.06 m; Mass = 76 ± 9 kg; 10 were right-hand dominant) volunteered to participate in this study. Each participant completed one data collection that lasted approximately two hours. Participants arrived at a university biomechanics lab, received instructions describing data collection procedures, and then provided informed consent. Data collection procedures were approved by the appropriate institutional review board prior to data collection. Each participant used his own tennis racquet throughout data collection.

In the biomechanics lab, eight calibrated high-speed video cameras (480 Hz; VICON, Centennial, CO,

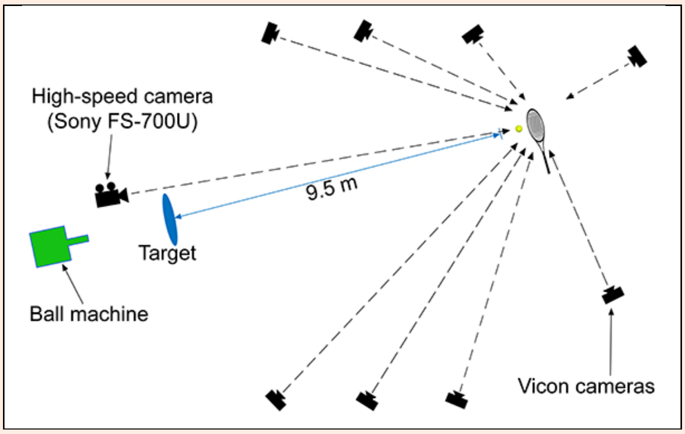

Figure 2. **A schematic showing the experimental set-up in the biomechanics laboratory, where hitting zone length, racquet head impact angle (i.e., open or closed racquet face), racquet trajectory before impact, horizontal and vertical racquet velocity before impact, and ball topspin angular velocity were measured.**

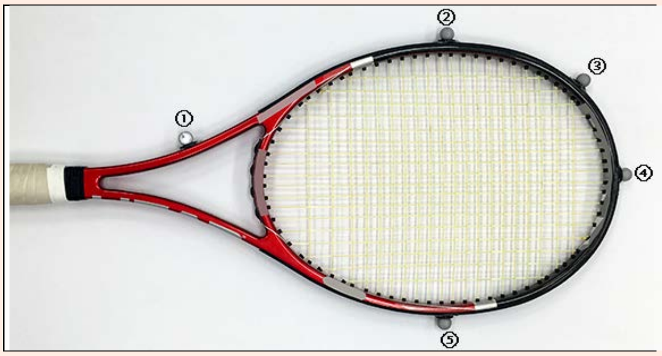

Figure 3. **A photograph showing the locations of the reflective markers that were applied to the tennis racquet and then used to measure various racquet kinematics during the laboratory data collection sessions.**

USA; Figure 2) were used to track the motion of a marked tennis racquet (Figure 3). The calibrated motion capture volume was approximately 3 m^3 and centered near the location of the expected ball-racquet impact. Although we did not quantify accuracy of the reconstructed spatial coordinates, we followed manufacturer guidelines in calibrating each motion capture volume. Previously, using a comparable calibration volume size and identical calibration procedures, we calculated the root mean square error of the coordinate reconstruction to be approximately 0.1 mm. We measured ball TAV in the lab using a different high-speed video camera (Frame Rate = 240 Hz; Exposure Time = 0.002 s; Resolution = 1920 x 1080 pixels; NEX-FS700U, SONY, Japan; Figure 2). The optical axis of the Sony camera was directed toward the expected position of ball-racquet contact and aligned nearly parallel to the expected direction of the forehand groundstrokes (Figure 2). The tennis balls were marked with two black orthogonal lines to facilitate the measurement of ball TAV. We quantified the spatial position of the marked racquet (Figure 3) to measure hitting zone length, racquet head impact angle, racquet trajectory before impact, and racquet horizontal and vertical velocity before impact.

To familiarize participants with the forehand topspin task (i.e., hitting topspin forehand groundstrokes, in the laboratory, using a marked racquet), participants hit approximately 10 forehand groundstrokes toward a target (a 1-m diameter hoop) that was 9.5 m from the subject and approximately 1.75 m high (Figure 2). A ball machine (Tennis Tutor Prolite, Sport Tutor Inc, Burbank, CA, USA) was positioned behind the target (Figure 2) and fed tennis balls to the participants at a speed of 11 m/s. After leaving the ball machine, the fed balls bounced once on the lab floor, to a height that was approximately shoulder high, and were struck by the participants. Participants were instructed to hit the forehands, at the target, at the same intensity as their best topspin forehand groundstroke, during a competitive tennis match. After the 10 familiarization forehands, participants were instructed to hit their best topspin forehand groundstroke, toward the target. Participants performed ten successful forehand groundstrokes, with 20 s between each stroke. Strokes were deemed successful when (1) the participant successfully hit the target area and (2) researcher and participant agreed that the stroke was representative of a high-quality, competitive, forehand groundstroke. A small number of trials were rejected because they did not meet the aforementioned criteria. Although we did not record the number of rejected forehand groundstrokes, we estimate that approximately 2 trials, on average, were rejected, per subject.

Following these lab trials, participants went to a nearby indoor tennis court to perform the forehand accuracy test. On this court, a tennis ball machine was positioned just behind the center mark on the opposite baseline and balls were fed, at 12.5 m/s (landing 0.5 m behind the service line), to the participants every 4 s. Participants hit 50 topspin forehand groundstrokes (25 cross-court and 25 down-the-line) toward a target area that was made up of three different sub-targets (Figure 4). During these on-court trials, we instructed the participants in an identical manner, relative to the laboratory trials: i.e., the participants were instructed to hit the forehands, at the target, at the same intensity they would use to generate their best topspin forehand groundstroke, in a competitive setting. Each shot was scored depending on which sub-target area the ball landed in (Target 1 =1 point; Target 2 = 2 points; Target 3 = 3 points). Earned points were totaled for all 50 forehand strokes, as well as for the 25 cross-court and 25 down-the-line strokes. As each groundstroke was performed, the same researcher visually scored each shot and totaled all scores. Forehand accuracy was quantified as the earned score, divided by the total possible score, multiplied by one hundred. This method of evaluating forehand groundstroke accuracy is similar to a previously described approach, used to evaluate serving accuracy (Fernandez-Fernandez et al., 2014). We chose to incorporate two shot directions to evaluate forehand accuracy because we believed this would more comprehensively reflect each subject's ability to accurately hit a forehand groundstroke in a competitive setting.

We quantified five explanatory variables: hitting zone length, racquet head impact angle, racquet trajectory before impact (relative to horizontal), and racquet horizontal and vertical velocity before impact. We quantified hitting zone length as the distance, in the horizontal plane, the racquet center (midpoint between Markers 2 and 5; Figure 3) traveled while the racket was between two orientations: 5˚ less than the orientation at impact (before impact) and 5˚ greater than the orientation at impact (after impact). In other words, we measured how far the racquet center exhibited quasi-translation, immediately before and after impact (Gensemer, 1985); we chose this 10˚ range of motion, because we believed it somewhat represented the previously-described hitting zone (Chafin and Moore, 1994; Gensemer, 1985; 1994). Racquet head impact angle was quantified as the angle depicted in Figure 1A, near the time of impact (Choppin et al., 2011). More specifically, the orientation between two lines: a line connecting Reflective Markers 2 and 5 (VICON; Figure 3), and a fixed horizontal axis (Figure 1A). Although the location of ball impact (on the racquet face), relative to the long axis of on the racquet, varies, this variation was expected to be random and not systematically influence our measured impact angles. Racquet trajectory, relative to horizontal, before impact was quantified as the mean orientation of the angle depicted in Figure 2B (angle from the horizontal), between 42 ms prior to impact and impact (this was an arbitrarily chosen duration that allowed for averaging of data on impact, as the racquet wobbles upon impact with the ball). For the variables of hitting zone length, racquet head impact angle, racquet trajectory before impact (relative to horizontal), and racquet horizontal and vertical velocity before impact, 10 discrete values were collected for each participant, representing the 10 lab trials.

Unfiltered data were used in calculating the explanatory variables, to avoid any smoothing of true signal, and we acknowledge potential risk for error associated with this approach (Knudson and Bahamonde, 2001; Tanabe and Ito, 2007). Because we measured the position data with such a high sampling rate (480 Hz), however, and the position data were expected to be quite accurate (RMS ~ 0.1 mm), we supposed that the analysis of raw data would suffice; to test this idea, we tested all trials for three of our subjects, by filtering the coordinate data using a 4th order, recursive, low-pass, Butterworth filter (17 Hz cutoff frequency). We compared three methods: (1) unfiltered, (2) filtering the entire trial, through impact, and (3) the linear extrapolation technique described by Knudson and Bahamonde (2001). For each of three subjects, the three aforementioned approaches resulted in nearly identical results, for three different tested explanatory variables: racquet trajectory before impact (relative to horizontal), and racquet horizontal and vertical velocities before impact. Results of these analyses are presented in Appendix A.

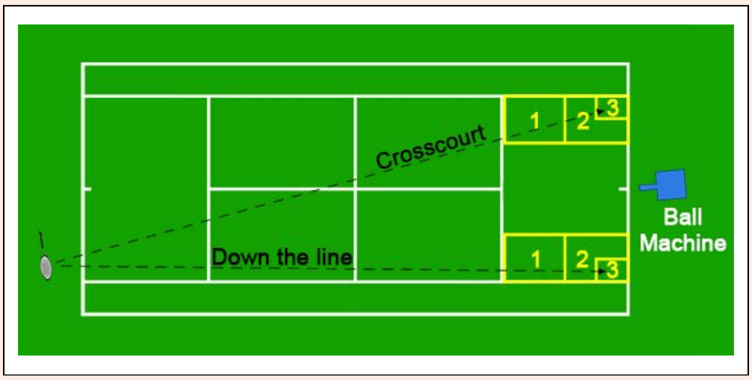

Figure 4. **A schematic showing how forehand accuracy was measured during the present study. The racquet indicates where each shot was taken from, and the numerical targets represent the targets for the cross-court and down-the-line forehand groundstrokes. Each shot that struck a target was awarded the number of points shown on that target.**

We quantified two response variables: ball TAV and forehand accuracy. We measured ball TAV using the aforementioned high-speed Sony camera (this was the only variable measured using this camera). We counted the number of video frames that elapsed during three complete ball rotations, immediately following racquet-ball impact. This number of frames was then divided by the frame rate (240 frames/s), to calculate time. The number of rotations (three) was then divided by time, which equaled the mean ball TAV (rotations per second). For ball TAV, 10 discrete values were collected and averaged for each participant (representing the 10 lab trials). Forehand accuracy was quantified as one value for cross-court strokes, one value for down-the-line strokes and one value for all of the strokes (total accuracy); these measures of accuracy were the only variables calculated on an actual tennis court.

Means and standard deviations for all of the explanatory and response variables were calculated. We used mixed model regression, with blocking on subject, to evaluate potential relationships between (1) the racquet kinematics (hitting zone length, racquet head impact angle, racquet vertical trajectory (relative to horizontal) before impact, and racquet horizontal and vertical velocity before impact) and (2) ball TAV. We used a multiple linear regression approach to evaluate potential relationships between the racquet kinematics and forehand groundstroke accuracy: cross-court, down-the-line, and total accuracy. For both the mixed model and multiple regression analyses, depending on the resulting p values, we used a forward-selection, stepwise, regression approach to construct a statistical model that best explained variation in the response variables. Scatterplots were used to evaluate the linearity assumptions for the relationships between predictor and response variables. An alpha level of 0.05 was set initially, however, to control the family-wise error rate, we adjusted each p value using Holm's step down method (Holm, 1979). We calculated coefficients of variation for each variable measured in the lab, to determine trial to trial variance for these measures, and these results are presented in Appendix B.

Results

Sample means and standard deviations for all of the explanatory and response variables are presented in Table 1. For ball TAV, a mixed model regression, with blocking on subject, that simultaneously related each measure of racquet kinematics to ball TAV, was statistically significant and explained most of the ball TAV variance ($p < 0.01$; $r^2 = 0.90$). Racquet head impact angle ($p < 0.01$) and racquet vertical velocity before impact ($p < 0.01$) dominated this model. Consequently, we chose to run a mixed model regression, using only racquet head impact angle and racquet vertical velocity before impact to predict ball TAV (Figure 5; $p < 0.01$; $r^2 = 0.90$). This model indicated (1) as racquet head impact angle decreases, ball TAV increases, and (2) as racquet vertical velocity before impact increases, ball TAV increases.

Table 1. Sample means (± standard deviations) for the explanatory and response variables that were measured during the present study.

Explanatory Variables					Response Variables			
Hitting zone length (mm)	Racquet HA at Impact (°)	Racquet VT BI (°)	Racquet HVBI (m/s)	Racquet VV BI (m/s)	Ball Spin Rate (RPM)	Total	Cross-Court	Down-the-Line
79.8 (8.6)	80.4 (3.6)	18.6 (4.3)	15.4 (1.4)	6.6 (2.2)	969 (375)	51.0 (7.6)	49.2 (9.2)	52.7 (8.7)

HA = Head Angle; VT = Vertical Trajectory Vertical Trajectory; HV = Horizontal Velocity; VV = Vertical Velocity; BI = Before Impact

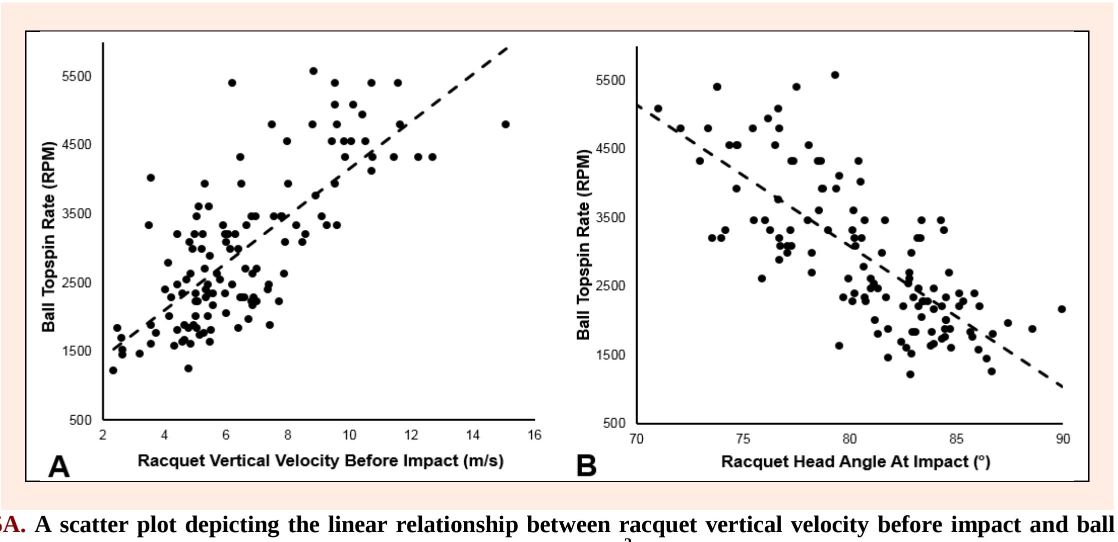

Figure 5A. A scatter plot depicting the linear relationship between racquet vertical velocity before impact and ball topspin angular velocity. These variables were positively related (*p* < 0.01; r^2 = 0.90), indicating that as racquet vertical velocity increased (i.e., a more vertical orientation), ball topspin angular velocity also increased. 5B. A scatter plot depicting the linear relationship between racquet head impact angle (i.e., open or closed racquet face) and ball topspin angular velocity. These two variables were negatively related (*p* < 0.01; r^2 = 0.90), indicating that as racquet head impact angle decreased, ball topspin angular velocity increased.

Regarding total forehand groundstroke accuracy (cross-court accuracy and down-the-line accuracy together), the multiple linear regression model, including all five explanatory variables (racquet kinematics), was not statistically significant ($p = 0.39$; $r^2 = 0.47$). Further, within this model, none of the explanatory variables were significant: the p values for hitting zone length, racquet head impact angle, racquet trajectory before impact, and racquet horizontal and vertical velocity before impact were 0.60, 0.12, 0.94, 0.52, and 0.45, respectively. Similarly, regarding cross-court accuracy, the multiple linear regression model, including all explanatory variables, was not statistically significant ($p = 0.09$; $r^2 = 0.69$). Only one of the explanatory variables was significant: racquet head impact angle ($p = 0.03$). Other p values for hitting zone length, racquet trajectory before impact (relative to horizontal), and racquet horizontal and vertical velocity before impact were 0.12, 0.60, 0.65, and 0.18, respectively. A simple linear regression relating racquet head impact angle and cross-court accuracy was not significant ($p = 0.06$, $r^2 = 0.29$). Somewhat similar results were observed for down-the-line accuracy. The multiple linear regression model including all explanatory variables was not statistically significant ($p = 0.58$; $r^2 = 0.36$), and none of the explanatory variables were significant: p values for hitting zone length, racquet head impact angle, racquet trajectory before impact, and racquet horizontal and vertical velocity before impact were 0.67, 0.43, 0.79, 0.50, and 0.86, respectively.

Discussion

The present results partially supported our a priori hypotheses. As hypothesized, racquet head impact angle and racquet vertical velocity before impact were significantly correlated to ball TAV (Figure 5). As racquet vertical velocity increased, ball TAV increased (Figure 5A). Also, as racquet head impact angle decreased (i.e., the racquet face became more closed), ball TAV increased (Figure 5B). Similarities between Figures 5A and 5B indicate that the associations are similar (i.e., the association between racquet vertical velocity and ball TAV, and the association between head impact angle and ball TAV); consequently, it is unclear which influences ball TAV more strongly (racquet vertical velocity or head impact angle). Unlike racquet head impact angle and racquet vertical velocity, hitting zone length, racquet trajectory before impact (relative to horizontal), and horizontal racquet velocity before impact were not statistically correlated to ball TAV or accuracy during the forehand groundstroke. Further, none of the measured racquet kinematics was significantly associated with any of the measures presently used to represent shot accuracy (total, down-the-line, or cross-court accuracy). Present measures of racquet kinematics were comparable with the same previously reported variables (as discussed later in this discussion), except racquet vertical velocity before impact, which was less than previously reported vertical velocities (Knudson and Blackwell, 2005; Takahasi et al., 1996). We are uncertain regarding the cause of this difference, however, we speculate that perhaps the difference was due to the nature of the target used in the laboratory: the target did not involve any requirement for accuracy of depth (Figure 2), so TAV was perhaps less important than it might be on an actual tennis court. We speculate the low vertical velocities that were presently observed could also have been due to different ball impact conditions (impact height and/or speed) that were used in this study.

The present results concerning racquet kinematics and forehand TAV show that racquet head impact angle and vertical velocity are important for producing ball TAV during the tennis forehand groundstroke. This corroborates mechanical logic and previous findings (Elliott and Marsh, 1989; Elliott et al., 1997; Takahashi et al., 1996) that indicated racquet vertical velocity and ball TAV are positively related during the forehand groundstroke. Perhaps, racquet trajectory is more influential on the vertical position (height) of the ball when it crosses the net; however, additional data are needed to confirm this idea. Before data collection, we hypothesized that steep vertical movement of the racquet (taught by many coaches as the low-to-high swing) would positively correlate to TAV, due to the racquet brushing up on the ball at a steeper trajectory. Although this idea is supported in the coaching literature (Gensemer, 1994), and is intuitive, it was not supported by our data. Future research is needed to elucidate this unexpected finding, and explain why racquet head angle and vertical speed might contribute more to ball TAV than racquet trajectory before impact, as defined in this study. Torque is required to create TAV, and torque is produced by applying a force to the ball that is directed away from the center of the ball (tangential force). The present results indicate that racquet head impact angle and racquet vertical velocity before impact are more effective at producing torque about the center of the ball than vertical trajectory of the racquet head. The present values for racquet head impact angle fit within previously reported values: the present values are slightly more closed than the angles near 90˚ reported by Elliott et al. (1989); however, the present values are slightly less closed than the mean of 21˚ reported by Choppin et al., (2011). In speculation, we suppose that this variation in values, for racquet head impact angle, could be due to differences in skill level, ball height at contact, ball speed, or intended target.

Another important consideration, related to the presently-observed racquet kinematics is that the variability of the trajectory of the incoming ball likely influences racquet kinematics. Also, racquet kinematics and ball TAV are both highly dependent on shot intentions during competition. Presently, incoming ball trajectory was nearly identical for every ball because the balls were fed from a ball machine with set parameters (relatively consistent trajectory and bounce location). The present results are limited to these highly homogenous conditions. The influence of racquet kinematics on ball TAV is likely dynamic and depends on multiple variables that change frequently during an actual tennis match (e.g., incoming ball speed, approach angle, timing of the hit, position of opponent, and intended purpose of the shot). If an incoming ball trajectory was lower or higher, or steeper or flatter, it would likely influence how a player adapts racquet impact angle and/or racquet trajectory, in order to produce a desired outcome (Knudson and Blackwell 2005; Landlinger et al., 2010). If the ball is being returned “on the rise,” after it has bounced, which is more common among highly skilled players, and not after the ball has reached its apex, a more horizontal racquet trajectory may be necessary, while still maintaining the ability to impart needed TAV on the ball. Of course, the player’s position also affects the trajectory of the incoming ball: if the player is deep in their own court or approaching the net.

Related to the preceding paragraph, although admittedly a bit outside the scope of this study, a steeper upward trajectory of the racquet, prior to impact, would theoretically reduce horizontal post-impact ball speed. This decreased horizontal ball speed, post-impact, reduces the opportunity that a tennis player has to take time away from an opponent with a faster (horizontal) and more penetrating (deeper in the court) shot. One way to optimize post-impact horizontal ball velocity and TAV is to decrease the racquet head impact angle, as well as the racquet vertical trajectory; i.e., hit the ball with a relatively closed racquet face and a relatively horizontal trajectory, facilitating more horizontal ball velocity and TAV.

One of the more interesting findings in the present study was a smaller than expected average hitting zone (the magnitude of quasi-linear displacement of the racquet immediately before and after ball impact). Given the cues that coaches are widely known to use (i.e., hit the ball in front of the body, shift weight forward and move into the shot, and extend the hitting zone) we expected the length of the hitting zone to be longer than the observed 79.8 ± 8.6 mm. Further, no relationship existed between hitting zone length, and ball TAV or forehand accuracy, for the current subjects. These findings cast doubt on the idea that a longer, rather than shorter, hitting zone is beneficial during tennis groundstrokes, especially for highly-skilled players. The idea that the racquet travels in a fairly straight path, immediately before and after ball impact, has been used in coaching and instructional books on tennis; e.g., Gensemer (1994) stated that a flattened arc swing, one that increases the linear distance through which the racquet moves immediately before and after ball contact, increases the accuracy of the struck ball. The present data contradict this idea and indicate that the so-called hitting zone occurs in a very short time, through a linear distance that is rather small (Table 1). Perhaps, skilled players, like the present participants, have an increased ability to time a shot, and minimize hitting zone length, while still hitting the ball in the desired direction. Moreover, our results indicated no relationship between hitting zone length and accuracy, with accuracy being comprised of a combination of direction and depth. We speculate that the hitting zone or flattened-arc may influence left-right accuracy most, while depth accuracy is most influenced by racquet head impact angle and corresponding ball TAV. A future study could confirm this speculation by considering hitting zone length and directional accuracy only.

There are a few limitations to consider. Participants used their own racquets, to ensure familiarity and consistency, and different racquets may have influenced swing speed, ball spin, racquet trajectory, and accuracy differently (Allen et al., 2016). Another limitation was the small homogenous nature of the sample: results might have varied for different skill levels of tennis players, and these results should only be applied to tennis players of skill levels comparable to the present participants. Additionally, the laboratory setting limited the ecological validity of this study; i.e., there may be kinematic differences, due to the laboratory setting alone (compared to hitting forehand groundstrokes on an actual tennis court during competition). Further, the forehand groundstrokes during this study were struck at shoulder height, which makes it relatively difficult to impart ball TAV. The study could have been improved by collecting all of the data on an actual tennis court, with dimensions much larger than those of our laboratory; however, we assumed that swing mechanics in a laboratory are similar to swing mechanics on an actual tennis court. Several previous publications regarding tennis biomechanics have also occurred in a laboratory setting (e.g., Seeley et al., 2008; 2011; Stepian et al., 2011).

Conclusions

This study evaluated potential relationships between five measures of racquet kinematics, and ball TAV and accuracy, for the tennis forehand groundstroke. The present findings indicated that (1) a more closed racquet head impact angle (between 70-85°) and (2) increased racquet vertical velocity before impact, are significantly correlated to increased ball TAV, during the forehand groundstroke. Other racquet kinematics (hitting zone length, racquet trajectory (before impact), and racquet horizontal velocity (before impact)) were not correlated to ball TAV or forehand accuracy, as measured as a combination of direction and depth. These findings confirm extensive previous research concerning racquet kinematics and ball TAV during the tennis forehand groundstroke.

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Key points

- The study confirmed previous research that two key racquet kinematic variables, near impact, are significantly correlated to ball topspin angular velocity, during the forehand groundstroke: racquet head impact angle (i.e., open or closed racquet face) and racquet vertical velocity, before impact.
- The trajectory (direction of resultant velocity) and horizontal velocity of the racquet head before impact, and length of hitting zone were not significantly correlated to ball topspin angular velocity, or shot placement accuracy, during the tennis forehand groundstroke, for skilled male players.
- Hitting zone length was smaller than expected for skilled tennis players performing the forehand groundstroke.

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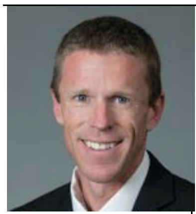

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Appendix A. **Results for three different explanatory variables, for three different subjects, processed using three different filtering approaches: (1) unfiltered, (2) filtering the entire trial, through impact, and (3) the linear extrapolation technique described by Knudson and Bahamonde (2001). The extrapolation and unfiltered technique resulted in results that were very similar.**

Racquet Trajectory Before Impact (°)			
Subject	**Filtered**	**Extrapolated**	**Unfiltered**
1	27.54	28.38	28.38
2	34.01	31.54	31.30
3	41.70	37.67	37.71
Racquet Horizontal Velocity Before Impact (m/s)			
Subject	**Filtered**	**Extrapolated**	**Unfiltered**
1	19.20	19.81	19.20
2	8.58	10.37	10.34
3	10.22	12.22	12.13
Racquet Vertical Velocity Before Impact (m/s)			
Subject	**Filtered**	**Extrapolated**	**Unfiltered**
1	9.58	10.33	10.37
2	7.65	8.01	7.99
3	7.05	7.16	7.16

Appendix B. **Coefficients of variation for every subject, describing within subject variance for every variable that was presently measured in the laboratory. These coefficients of variation are quite comparable to previously reported coefficients of variation describing intrasubject variability for forehands performed on an indoor tennis court (Knudson & Blackwell, 2005).** HA = Head Angle; VT = Vertical Trajectory Vertical Trajectory; HV = Horizontal Velocity; VV = Vertical Velocity; BI = Before Impact

Subject	Hitting Zone Length	Racquet HA at Impact (°)	Racquet VT BI (°)	Racquet HV BI (m/s)	Racquet VV BI (m/s)	Ball Spin Rate (RPM)
1	15.9	3.8	18.4	5.0	13.2	9.9
2	19.7	2.5	7.7	9.0	9.7	21.6
3	3.7	2.3	14.2	10.7	21.5	18.5
4	21.9	4.8	14.3	10.8	8.9	21.4
5	16.2	3.2	16.6	7.7	11.3	17.4
6	34.9	2.3	9.8	4.2	7.8	12.1
7	3.6	1.9	7.0	4.1	7.0	22.8
8	10.3	2.8	28.8	6.8	20.8	11.2
9	22.1	2.5	22.3	7.3	25.0	20.6
10	38.0	2.9	14.3	7.0	26.9	7.2
11	34.8	2.5	11.9	6.1	10.0	11.6
12	18.5	3.2	9.6	3.7	6.4	11.5
13	36.1	2.3	18.9	4.8	22.4	7.8
Mean	21.2	2.8	14.9	6.7	14.7	14.9
St Dev	11.8	0.8	6.2	2.4	7.5	5.6