

Key factors and timing patterns in the tennis forehand of different skill levels

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Abstract

The main purpose of the present study was to quantify and compare selected kinematic variables and their timing during the tennis forehand of different skill levels. An eight-camera 400 Hz, Vicon motion analysis system recorded kinematic data of six ATP-professionals (elite) and seven high performance (HP) players when shots were played cross court and down the line. Timing of the maximum angles, linear and angular velocities was measured prior to and after impact. A total of twelve strokes per subject were analyzed from the beginning to the end of horizontal racquet movement. Significant differences ($p < 0.01$) and large effect sizes were observed between elite and HP players in the timing of maximum pelvis (-0.075 ± 0.008 vs. -0.093 ± 0.012 s) and trunk angular velocities (-0.057 ± 0.004 vs. -0.075 ± 0.011 s) before impact. The elite group showed a tendency ($p < 0.05$) towards higher peak horizontal shoulder (3.0 ± 0.4 vs. 2.5 ± 0.4 m·s⁻¹) and racquet velocities (33.1 ± 2.4 vs. 31.1 ± 1.9 m·s⁻¹) compared to the HP players. Depending on the situation (cross court vs. down the line), different peak hip, racquet and separation angles were found for both groups. Similar peak values were detected between groups for maximum angular velocities and displacement of key variables that had been selected for analysis. The findings of this study can be vital for successful player development, improved performance or injury prevention. The later occurrence of maximum angular pelvis and trunk rotations were the main reasons for the tendency towards higher horizontal shoulder and racquet velocities in the elite group.

Key words: Biomechanics, racquet speed, kinematics, proximal-to-distal sequencing.

Introduction

Tennis coaches and players are constantly striving to improve their strokes from a technical point of view hoping that one of the key factors of the game's technique, which is racquet speed, will become greater, and therefore, will make the players' "weapons" more effective. Crespo and Higuera (2001) pointed out that the ability to hit the ball with immense power is a distinguishing feature of the modern game. Younger players still need to develop this ability, which, among other skills, might separate the elite from the high performance athletes.

From a biomechanical aspect, motions and positions of various joints that are inefficient can either be detrimental to the speed and the spin of the ball or may even increase the risk of injury (Kibler and Van der Meer, 2001). One of the most important principles responsible for fast strokes is "the summation of speed principle" (Bunn, 1972; Marshall and Elliott, 2000; Putnam, 1993).

It simply states that the central segments that are closer to the body initiate a motion and provide a platform to produce maximum speed at the end of the distal segment. The proximal-to-distal sequencing pattern, as the main characteristic of this principle, has been described in many overhead activities, including the tennis serve (Bahamonde, 2000; Elliott et al., 1995; Fleisig et al., 2003). A study of the tennis serve and the squash forehand drive by Marshall & Elliott (2000) included long axis rotations, an important factor for describing the complexity of tennis strokes, which was often neglected in previous proximal-to-distal sequencing studies. Their study identified internal rotation as the major contributor to racquet head speed in both motions, a factor also found to be the main parameter to differentiate slow and fast servers (Tanabe and Ito, 2007). In a kinematic study on the tennis forehand stroke, the maximum internal rotation velocity was found to occur quite late in the forward swing phase (Takahashi et al., 1996). Although the forehand groundstroke is the second most frequent stroke in service games on a professional level (Johnson, 2006), research on kinematic coordination patterns in the forehand is limited (Elliott et al., 1989; Takahashi et al., 1996).

Interestingly, sports studies with similar motion patterns like golf or baseball give more insight into kinematic parameters and respective temporal data. In golf, the following main results have been found: 1) higher angular velocity for club shaft, shoulder internal rotation and elbow extension; 2) different temporal order for selected peak angular velocities when comparing pro and amateur golfers (Zheng et al., 2008); 3) gender-related differences for thorax and pelvis motion at different phases of the swing (Horan et al., 2010); and 4) group differences and moderate relationships between an increase in ball velocity and maximum torso-pelvic separation angle and maximum upper torso rotation velocity (Myers et al., 2008). The latter aspect is frequently a topic of discussion among tennis coaches; namely that in tennis, a greater maximum torso-pelvic separation angle increases torso rotation velocity and, consequentially, racquet and ball velocity. However, but has not been explicitly studied yet. Moreover, in baseball batting, where the coiling or loading phase is also comparable to the backswing in tennis groundstrokes, it has been demonstrated that a high bat speed can be achieved when segment rotations are properly timed (Welch et al., 1995).

Similar to other sports, the sequential coordination of body segments during the forward swing should lead to an increased end point speed of the tennis racquet. Despite high interest in the theory of racquet speed creation

among tennis coaches and the high importance of the forehand stroke as a performance limiting factor in the game, to our knowledge, there is no study comparing proximal-to-distal sequencing patterns of the forehand with respect to elite vs. high performance playing levels. Therefore, the main aim of this study was to identify and compare key mechanical features and their timing of forehand groundstrokes between ATP-professionals (elite) and high performance youth players when shots were played cross court and down the line.

It was mainly hypothesized that elite players would achieve: (1) higher maximum horizontal and vertical racquet velocities; (2) higher maximum angular velocities of the trunk and the shoulder; (3) greater maximum displacement of the shoulders and a greater separation angle during the forward swing; and (4) a different temporal order for selected peak angular velocities than high performance players.

Methods

Participants

Six elite male players with an average personal best ATP-ranking of 347 and seven high performance male youth players with a top 15 national youth ranking at the time of testing, volunteered to participate in the study. The two groups were significantly different in age (elite vs. high performance, mean (SD): 23 (2.3) vs. 16.3 (0.5) years, $p < 0.01$), but similar in mass (78.2 (11.6) vs. 72.8 (8.2) kg, $p > 0.05$) and height (188.1 (8.9) vs. 185.9 (5.8) cm, $p > 0.05$). All participants gave their written consent after they had been briefed on the procedures of the study. The study was approved by the local ethics committee and there were no reported injuries during the time of the study.

Testing procedure

After an individual warm-up and explanations about the experimental procedure, participants could hit as many practice strokes as needed to familiarize themselves with the testing environment. Participants used their own racquets during the testing process. A ball machine controlled pre-impact ball horizontal velocity ($20 \text{ m}\cdot\text{s}^{-1}$) and trajectory. New tennis balls were projected down the line when participants had to play cross court and vice versa. Before testing, subjects were encouraged to hit the ball with the same velocity and action as they would in a match. They were instructed to hit two series of ten forehands cross court and down the line (4 x 10 strokes) to a target area (randomized order). With respect to their individual preparation for a successful forehand, no instructions were given in terms of foot placement (stance). Participants had a two minute break after each series. To derive representative and accurate kinematics of the recorded forehand strokes, the six fastest cross court and down the line shots that landed in the target area were chosen for analysis. Therefore, a total of 12 strokes per subject were considered for analysis in this study.

Data collection

A total of 39 reflective markers (25mm in diameter) were placed on bony landmarks (Plug-In Gait Marker Set,

Vicon Peak, Oxford, UK) of every participant for kinematic analysis. Four additional markers (14mm in diameter) were placed on the tennis racquet of each subject (racquet head, shaft, at 3 and 9 o'clock positions). Participants wore tight shorts and no shirts in order to limit movement of the markers from their anatomical landmarks during the forehand motion. (Note: during high dynamic movements, skin attached markers can produce errors due to movement of the skin, and muscle (Gordon and Dapena, 2006)). Data was captured with eight Vicon MX 13 cameras (Vicon Peak, Peak, Oxford, UK), sampling at 400 Hz. The cameras were strategically positioned around one side of the court (3 cameras behind the baseline, 1 camera at each side line, and 3 overhead cameras on a traverse at 4m height in front of the player) to ensure optimal marker identification. The centre of the baseline was used as the origin of the global coordinate system where the y-axis was pointing forward to the net, the x-axis was positive to the right, and z was vertical. Three-dimensional coordinates of the 43 markers were reconstructed with the Nexus software (Nexus 1.3, Vicon, Oxford, UK) and data was filtered with a Woltring filter (MSE of 10) (Woltring, 1986). Since the entire swing was filtered, which can lead to over-smoothing (Knudson and Bahamonde, 2001), systematic errors might have occurred. However, in preliminary data analysis we experienced that a high filming rate of 400 Hz is beneficial in terms of creating smaller end point errors. As mentioned by Tabuchi et al. (2007), the sampling rate and the filter affect time-speed profiles. In order to calculate the joint centre positions, a three-dimensional model (Plug In Gait Model, Vicon Peak, Oxford, UK) dividing the body into lower and upper body models was used (Davis et al., 1991). Lower and upper body models were defined as described by Wagner et al. (2010).

Phase definition, variables of interest, and timing

Relevant data was analyzed during the forward swing of the stroke, which was determined as the phase from the first horizontal (towards the opponent) movement of the racquet shaft to the end of the forward racquet head movement in a horizontal direction. The phase from impact to the end of horizontal racquet movement is also considered the first phase of the follow through. Impact was defined as the point where the first ball/racquet contact occurred. It was identified with a Basler digital high speed camera (100 Hz) and verified with racquet coordinate data. Kinematic parameters were selected based on previous tennis studies (Bahamonde and Knudson, 2003; Elliott et al., 1989; 1997; Fleisig et al., 2003; Takahashi et al., 1996), other sports (golf, baseball) and discussions with international tennis experts. Thus, the kinematic variables of interest during the forward swing for the cross court and down the line situations were as follows: 1) maximum horizontal velocity of the racquet head, shoulder, elbow, and wrist; 2) maximum vertical racquet head velocity; 3) maximum racquet, shoulder, and hip alignment, and maximum separation angle (Figure 1A); 4) maximum angular velocity of the pelvis and the trunk (counter-clockwise rotation) (Figure 1B); 5) maximum internal (forward) rotation of the shoulder (Figure 1B); 6) maximum rear leg, and elbow extension velocity (Figure

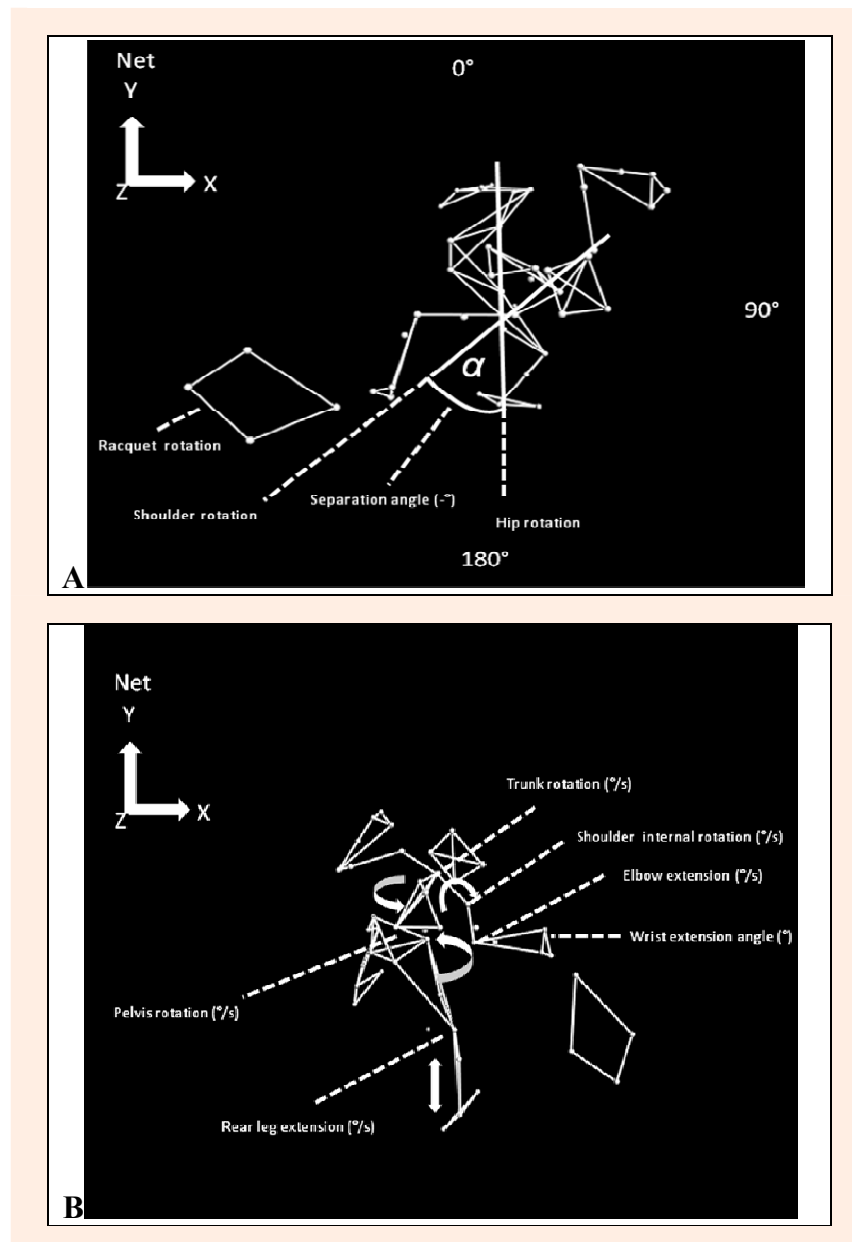


Figure 1. (A) Illustration of racquet rotation, hip alignment, shoulder alignment and separation angle at the beginning of the forward swing. (B) Illustration of wrist extension angle and different angular velocity variables that were selected for analysis during the forward swing.

1B); 7) maximum wrist extension angle (Figure 1B). Although the authors accepted the maximum values of shoulder internal rotation velocity, its results need to be interpreted with caution due to the model used (Elliott et al., 2007; 2008).

When the hips, the shoulders, or the racquet rotated backwards, such that they were perpendicular to the baseline, (e.g. at the beginning of the forward swing), a 180° angle was recorded (Figure 1A). A greater rotation of the shoulders compared to the hips resulted in a greater negative *separation angle*, a term used for the angular difference between the lines representing the shoulders and the hips (Elliott, 2003).

Timing of the maximum angles, linear, and angular velocities was measured as time prior to and after impact (Fleisig et al., 2003; Marshall and Elliott, 2000; Welch et al., 1995).

Statistical analysis

All statistical analyses were performed using SPSS 15.0. (SPSS Inc., Chicago, Illinois, USA). All variables were tested for normal distribution and means and standard deviations of the variables were calculated for descriptive statistics. Two-way analysis of variance (elite, high performance) with repeated measures on type of shot (cross court, down the line) detected statistical differences and effects in selected kinematic variables. Due to the large number of comparisons, the level of significance was set at $\alpha < 0.01$ and effect size (η^2) was defined as small for $\eta^2 > 0.01$, medium for $\eta^2 > 0.06$, and large for $\eta^2 > 0.14$ (Cohen, 1988).

Results

Mean forward swing time of the tennis forehand for the

Table 1. Tennis forehand kinematics (mean \pm SD) of elite and high performance players in the cross court (Cross) and down the line (DL) situation.

Variable	Elite (n=6)			High Performance (n=7)		
	Cross	DL	Mean	Cross	DL	Mean
Maximum angular displacement (°)						
Shoulder alignment (°)	195.9 (10.8)	195.8 (10.2)	195.8 (10.0)	194.5 (8.4)	197.5 (8.7)	196.0 (8.4)
Hip alignment (°)	170.4 (9.4)	174.7 (10.4) #	172.6 (9.7)	164.1 (9.3)	171.1 (7.2) #	167.6 (8.8)
Racquet angle (°)	193.5 (24.5)	197.5 (22.6) #	195.5 (22.6)	188.0 (17.3)	195.8 (17.8) #†	191.9 (17.4)
Wrist extension (°)	89.6 (11.3)	87.7 (10.0)	88.7 (10.2)	84.6 (7.1)	84.4 (9.4)	84.5 (7.8)
Separation angle (°)	-28.7 (9.5) #	-25.4 (8.9)	-27.0 (8.9)	-34.7 (10.1) #	-31.2 (9.9)	-33.0 (9.8)
Maximum velocity (m·s⁻¹)						
Hip (m·s ⁻¹)	1.4 (0.1)	1.5 (0.3)	1.5 (0.2)	1.4 (0.4)	1.4 (0.2)	1.4 (0.3)
Shoulder (m·s ⁻¹)	3.1 (0.5)	3.0 (0.3)	3.0 (0.4) *	2.6 (0.4)	2.4 (0.3)	2.5 (0.4)
Elbow (m·s ⁻¹)	6.3 (0.6)	6.2 (0.6)	6.3 (0.6)	6.0 (0.5)	5.7 (0.5)	5.9 (0.5)
Wrist (m·s ⁻¹)	11.1 (0.7)	10.9 (0.9)	11.0 (0.8)	10.5 (0.8)	10.0 (1.1)	10.3 (1.0)
Racquet head-horizontal (m·s ⁻¹)	34.4 (2.3) #	31.7 (1.7)	33.1 (2.4) *	32.5 (0.9) #	29.7 (1.4)	31.1 (1.9)
Racquet head-vertical (m·s ⁻¹)	18.3 (2.4)	19.2 (2.9) †	18.7 (2.6)	19.3 (1.2)	19.0 (1.6)	19.2 (1.3)
Maximum angular velocity (°/s)						
Shoulder int.rot. (°/s)	825 (53)	762 (100)	793.7 (83.0)	803 (233)	780 (220)	791.4 (218.1)
Elbow extension (°/s)	279 (102)	276 (99)	277.5 (95.9)	319 (42)	306 (58)	312.5 (49.0)
Trunk rot. (°/s)	757 (45)	733 (112)	745.0 (82.1)	748 (68)	708 (75)	728.0 (71.7)
Pelvis rot. (°/s)	547 (36) #	534 (47)	540.5 (40.5)	521 (63) #	490 (64)	505.2 (63.2)
Rear leg extension (°/s)	-237 (66)	-223 (63)	-230.2 (61.7)	-291 (107)	-250 (71)	-270.3 (89.7)

* Elite group tends to be different from High Performance group: shoulder ($F = 8.454$, $p = 0.014$, $\eta^2 = 0.435$), and racquet head ($F = 5.371$, $p = 0.041$, $\eta^2 = 0.328$). # Main shot effect: hip alignment ($F = 26.912$, $p = 0.000$, $\eta^2 = 0.710$), racquet angle ($F = 47.583$, $p = 0.000$, $\eta^2 = 0.812$), separation angle ($F = 28.916$, $p = 0.000$, $\eta^2 = 0.724$), racquet head velocity ($F = 68.203$, $p = 0.000$, $\eta^2 = 0.861$); tendency: pelvis rotation ($F = 5.982$, $p = 0.032$, $\eta^2 = 0.352$). † Interaction effect tendency with Racquet angle of High Performance DL different to Cross ($F = 5.041$, $p = 0.046$, $\eta^2 = 0.314$) and with racquet head vertical velocity of Elite DL different to Cross ($F = 4.934$, $p = 0.048$, $\eta^2 = 0.310$).

cross court and down the line situation did not vary between elite (0.324 ± 0.086 s) and high performance players (0.326 ± 0.064 s). Table 1 lists the means and standard deviations of maximum angular displacement data, maximum velocities, and maximum angular velocities.

No group differences were found for maximum angular displacement data during the forward swing. In the down the line situation, both groups rotated their hips and racquets further backwards ($p < 0.01$), but reduced their separation angle. The high performance players showed a tendency towards an interaction effect for maximum racquet angle ($p < 0.05$, $\eta^2 = 0.314$), which demonstrated a further increased value from cross court to

down the line compared to the elite group (Table 1).

A tendency towards a higher maximum horizontal racquet head velocity for the elite players (33.1 ± 2.4 vs. 31.1 ± 1.9 m·s⁻¹, $p < 0.05$, $\eta^2 = 0.328$) was found. Calculations for the peak horizontal velocity of the shoulder also tended to be higher for the elite group ($p < 0.05$, $\eta^2 = 0.435$). Both groups showed higher values for horizontal racquet head velocity when comparing the cross court to the down the line situation ($p < 0.01$), while the elite players demonstrated a tendency towards increased values for their maximum vertical racquet velocity ($p < 0.05$, $\eta^2 = 0.314$) when playing down the line.

There were no differences in the selected

Table 2. Timing (mean \pm SD) of key events expressed as time (s) prior to/after impact during the tennis forehand of elite and high performance players in the cross court and down the line (DL) situation. The variables on the left column are listed in order of their peak values during the forward swing of the elite players.

Variable	Elite (n=6)			High Performance (n=7)		
	Cross	DL	Mean	Cross	DL	Mean
Max. hip alignment angle	-.253 (.086)	-.232 (.051)	-.243 (.068)	-.235 (.046)	-.236 (.034)	-.236 (.039)
Max. shoulder alignment angle	-.234 (.051)	-.228 (.046)	-.231 (.046)	-.213 (.037)	-.214 (.027)	-.214 (.031)
Max. separation angle	-.179 (.077)	-.158 (.082) #	-.168 (.077)	-.151 (.020)	-.145 (.020) #	-.148 (.019)
Max. racquet rotation angle	-.157 (.047)	-.135 (.037)	-.146 (.042)	-.135 (.047)	-.131 (.040)	-.133 (.042)
Max. hip linear velocity	-.100 (.048)	-.093 (.049)	-.097 (.046)	-.109 (.070)	-.116 (.062)	-.113 (.064)
Max. pelvis angular vel.	-.076 (.008)	-.074 (.009)	-.075 (.008) *	-.091 (.013)	-.095 (.012)	-.093 (.012)
Max. rear leg extension velocity	-.071 (.035)	-.066 (.040)	-.069 (.036)	-.081 (.032)	-.101 (.024)	-.091 (.029)
Max. trunk angular velocity	-.058 (.002)	-.056 (.005)	-.057 (.004) *	-.074 (.012)	-.076 (.011)	-.075 (.011)
Max. wrist extension angle	-.057 (.011)	-.053 (.011)	-.055 (.011)	-.054 (.010)	-.058 (.014)	-.056 (.012)
Max. shoulder linear vel.	-.045 (.008)	-.045 (.009)	-.45 (.08) *	-.060 (.016)	-.062 (.017)	-.061 (.016)
Max. elbow linear vel.	-.040 (.006)	-.037 (.004) #	-.039 (.005)	-.042 (.005)	-.038 (.008) #	-.040 (.007)
Max. wrist linear vel.	-.038 (.005)	-.035 (.005) #	-.037 (.005)	-.041 (.004)	-.038 (.005) #	-.040 (.004)
Max. racquet head horizontal velocity	-.003 (.000)	-.002 (.001)	-.002 (.000)	-.003 (.001)	-.003 (.000)	-.003 (.001)
Impact time (s)	.263 (.094)	.256 (.078)	.259 (.082)	.252 (.065)	.259 (.055)	.256 (.058)
Max. shoulder internal rotation velocity	.025 (.007)	.023 (.014)	.024 (.011)	.020 (.014)	.027 (.012)	.024 (.013)
Max. elbow extension velocity	.031 (.040)	.040 (.027)	.035 (.033)	.014 (.051)	.010 (.052)	.012 (.049)
Max. racquet head vertical velocity	.038 (.006)	.040 (.006)	.039 (.006)	.033 (.009)	.033 (.008)	.033 (.008)

* Elite group significantly different from High Performance group: pelvis ($F = 9.857$, $p = 0.009$, $\eta^2 = 0.473$), trunk ($F = 13.526$, $p = 0.004$, $\eta^2 = 0.552$); tendency: shoulder ($F = 4.968$, $p = 0.048$, $\eta^2 = 0.311$). # Main shot effect for DL shot: elbow ($F = 86.182$, $p = 0.000$, $\eta^2 = 0.887$); tendency: separation angle ($F = 5.136$, $p = 0.045$, $\eta^2 = 0.318$), and wrist ($F = 4.989$, $p = 0.047$, $\eta^2 = 0.312$).

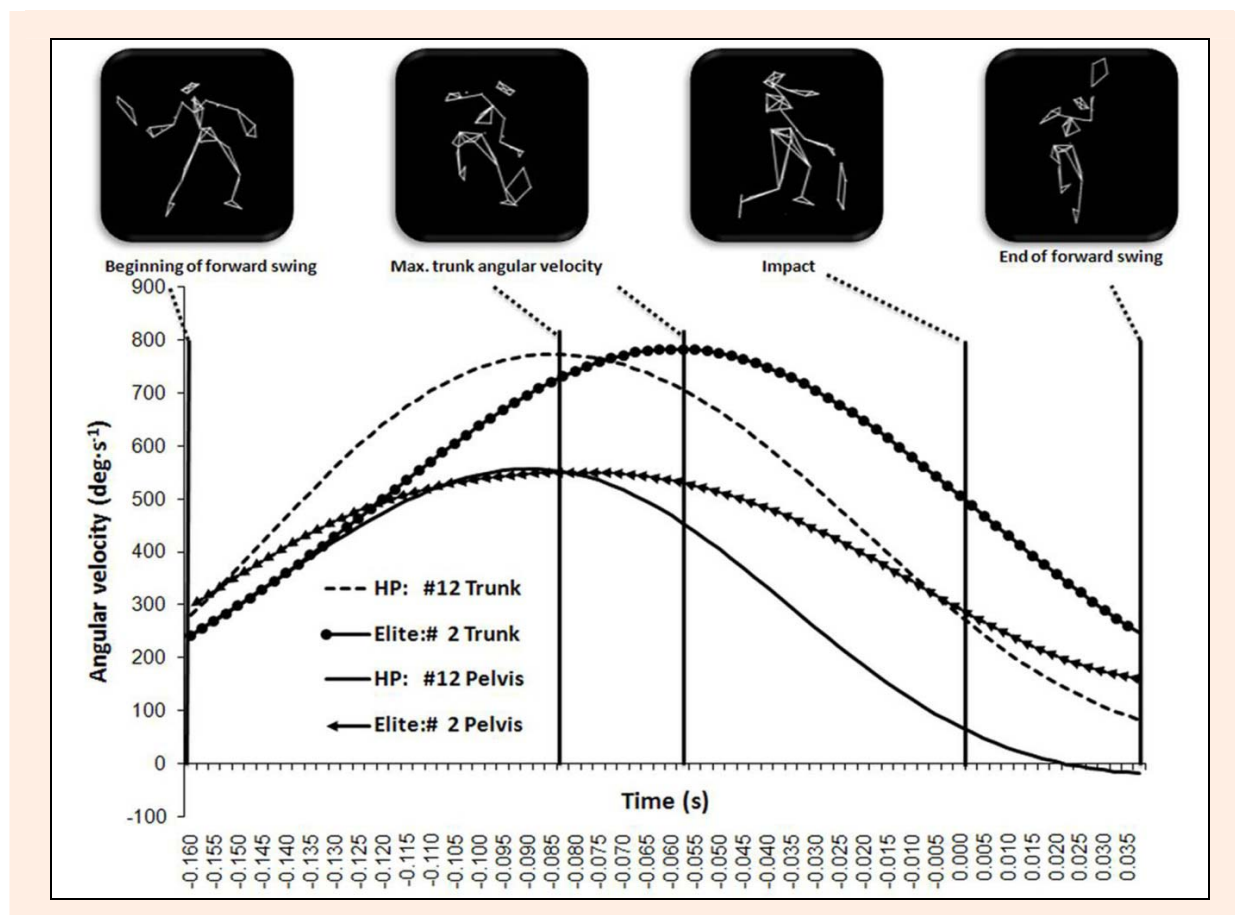


Figure 2. A representative example of maximum pelvis and trunk angular velocities in a forehand cross court stroke of an elite (participant #2) and a high performance player (participant #12).

maximum angular velocity variables between elite and high performance players. However, elite and high performance players tended to increase their pelvis rotation velocity in the cross court situation ($p < 0.05$, $\eta^2 = 0.352$.)

Table 2 displays the timing results of the analyzed key events in time (s) prior to/after the event of impact. The average time of impact did not vary between groups. The timing of maximum angular pelvis and trunk rotation velocities differed between elite and high performance players (both $p < 0.01$). The latter reached their maximum values earlier for these two mentioned variables (Figure 2). The elite group generally also tended to show a later appearance of linear peak shoulder velocity ($p < 0.05$, $\eta^2 = 0.311$) while linear peak elbow velocity occurred earlier in the cross court situation of both groups ($p < 0.01$). The only two variables that varied from the elite timing order were maximum rear leg extension velocity (occurred earlier in HP group) and maximum elbow extension velocity (occurred before shoulder internal rotation in HP group). The rest of the chosen variables showed similar results for peak values with respect to sequence and appearance. All players demonstrated a complete proximal-to-distal sequence of peak linear velocities (Table 2, Figure 3), and they reached their maximum internal rotation velocity of the shoulder after impact (Table 2, Figure 4).

Discussion

Maximum angular displacement and timing

Since Myers et al. (2008) found out that the maximum torso-pelvis separation angle increases with the ball speed of golfers, and Zheng et al. (2008) reported a greater trunk rotation for the pro golf group compared to the high handicap group, one could have expected similar findings in the present study. This, however, was not the case since measures for maximum separation angle and shoulder alignments were comparable between groups (Table 1); nevertheless, these values were similar to findings of a previous study by Takahashi et al. (1996). The current results also indicate that the magnitude of rotation for the racquet and the hips did not divide the elite from the high performance players. However, a more closed stance type which is usually used in the down the line situation could have been one of the reasons for a greater displacement of the racquet and the hips in both groups compared to the cross court situation. Results did give valuable information about the timing of peak angles which help facilitate a proper biomechanical description of the forward swing in the tennis forehand. Shortly after the end of the back-swing, both groups reached their maximum displacement of the hips, followed by the shoulders. The timing of the maximum separation angle later in the stroke points out that the hips must have started the counter-clockwise rotation towards the ball earlier than the shoulders; therefore, probably increasing the pre-stretch on the trunk. The even later appearance of peak angular racquet rotation demonstrates that the racquet tends to lag behind; thus, also pre-stretching the shoulder musculature which should

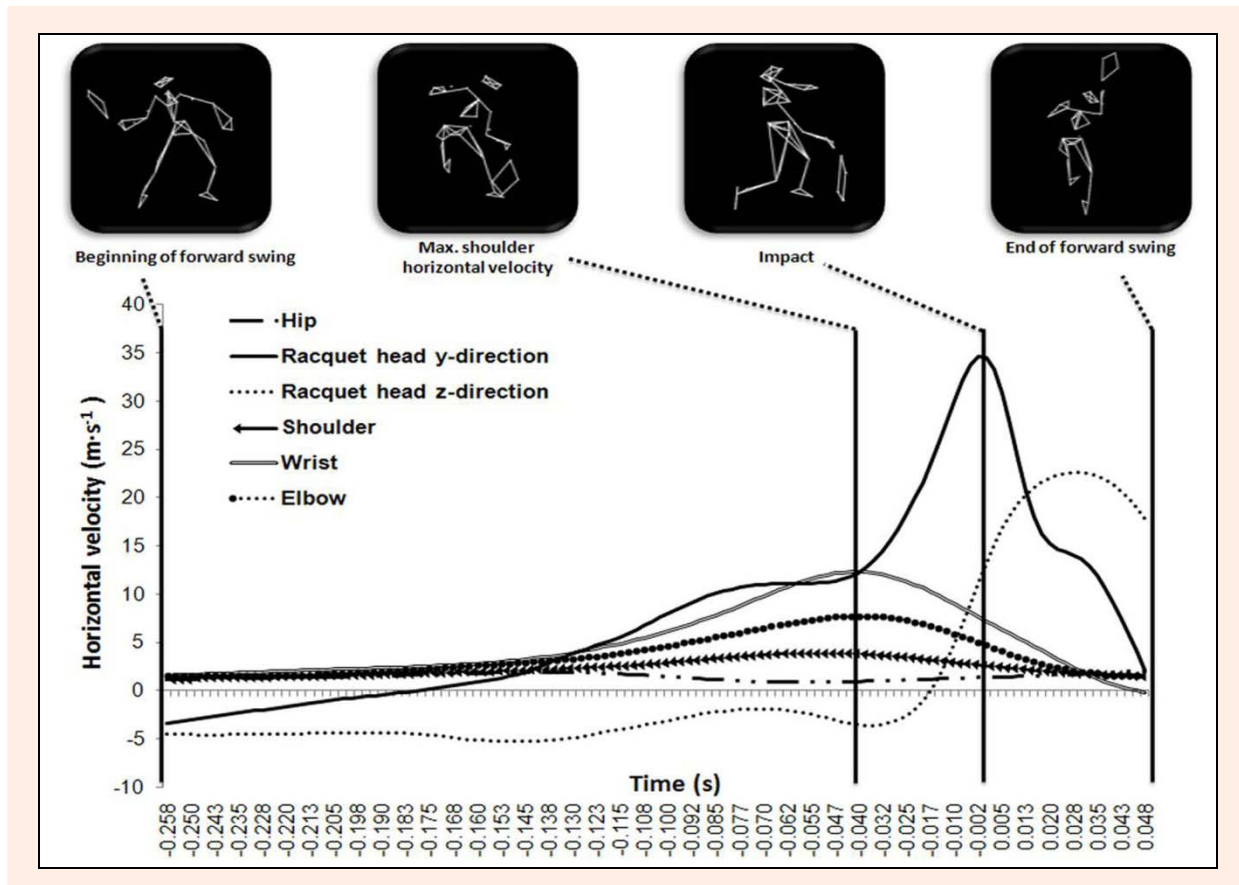


Figure 3. A representative proximal-to-distal sequencing pattern of maximum linear velocities ($\text{m}\cdot\text{s}^{-1}$) in the tennis forehand of an elite player (personal best ATP ranking: 167).

enhance their capacity to generate more force (Bahamonde and Knudson, 2003; Elliott, 2003; Putnam, 1993). Bahamonde and Knudson (2003) also measured large peak shoulder internal rotation and horizontal adductor torques at this beginning of trunk forward rotation. Moreover, the hyper extended wrist, which reached its peak about 55 milliseconds before impact, should have put additional stretch on the forearm of all players; therefore, help generate wrist and racquet speed.

Maximum linear velocities and timing

It seems that after vigorous hip and trunk rotation, both groups took advantage of their well-coordinated movements. There is a complete proximal-to-distal sequence of maximum joint linear velocities (Table 2, Figure 3). The hip, shoulder, elbow, wrist, and the racquet reached their peak speeds in sequence, therefore confirming “the summation of speed principle” (Bunn, 1972; Marshall and Elliott, 2000; Putnam, 1993). A comparison of the single and multi-segment forehand, by Elliott et al. (1989), showed similar results. Due to the fact that maximum elbow and wrist velocities were comparable between the elite and the high performance players, one can assume that the elite group’s tendency towards higher shoulder velocities contributed to the obvious trend of increased horizontal racquet velocities in this group. In addition, earlier peak elbow velocities do not explain the increased racquet speed for both groups when balls were played cross court instead of down the line (Table 1). However, both groups reached their maximum vertical racquet head

velocity after impact, which indicates an increasing swing path (steeper racquet trajectory) through impact and into the follow through. In general, the racquet swing path will always depend on the type of stroke and the level of spin a player wants to impart on the ball (Elliott et al., 2009). Nevertheless, the elite players tended to increase their racquet velocity in the vertical direction when playing down the line. Elliott et al. (1997) also found increasing vertical racquet velocities from flat to topspin to lob strokes. It seems that the elite players in this study imparted more topspin to the ball when hitting down the line; therefore, increasing the margin for error over the net (Brody, 2006). Brody (2006) also pointed out why the cross court shot was safer (mainly due to the longer distance); thereby, giving a meaningful general reason why shots in the present study were played faster in the cross court situation (Table 1).

Maximum angular velocities and timing

Since the maximum angular velocities of all selected variables did not vary between groups, it is plausible that their timing played a decisive role in the stroke production of the forehand. While the rear leg initiated the early maximum forward movement of the hip, maximum pelvis rotation occurred later in both groups, consistent with the work of Iino and Kojima (2006). Peak values of rear leg extension almost coincided with maximum pelvis angular velocities in the high performance group. However, the rear leg drive is mainly responsible for the pelvis and the later trunk rotation in the tennis forehand (Iino and

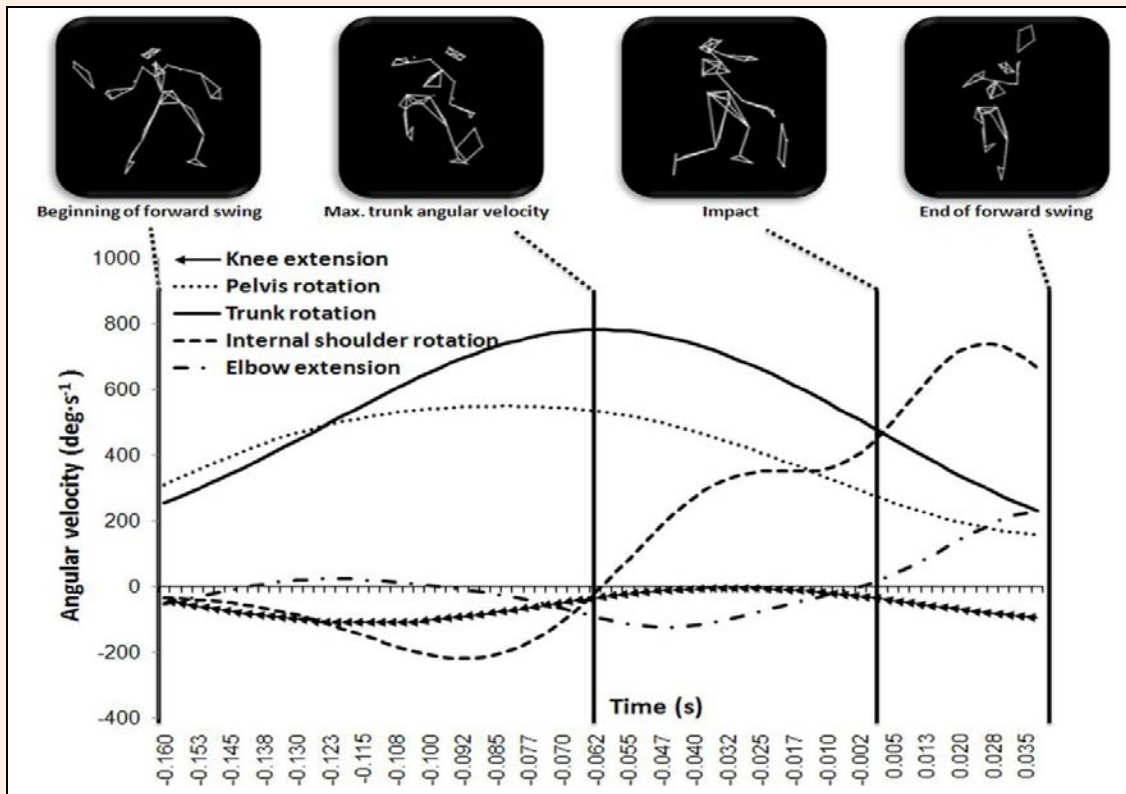


Figure 4. A representative time course of joint angular velocities ($\text{deg}\cdot\text{s}^{-1}$) in the tennis forehand of an elite player (personal best ATP ranking: 250).

Kojima, 2001). During the extension of the back leg, the rotational velocity of the pelvis in the elite group increased until it reached a maximum mean of about $541 \text{ deg}\cdot\text{s}^{-1}$, 0.075 seconds prior to ball contact. This timing of peak hip rotation velocity was exactly the same in a study of baseball batting (Welch, 1995). Nevertheless, the high performance players reached their maximum pelvis angular velocity significantly earlier ($-0.093 \pm 0.012 \text{ s}$). The same results with respect to timing (Elite: $-0.057 \pm 0.004 \text{ s}$ vs. High performance: $-0.075 \pm 0.011 \text{ s}$) were found for the trunk rotational velocity, a parameter which has been found to strongly correlate with racquet velocity, regardless of skill level and the type of stance used in a previous study (Bahamonde and Knudson, 1998). The comparison of pelvis and trunk rotations (Figure 2) gives a plausible explanation why the elite players tended to create greater horizontal racquet speeds. Even though maximum peak values of the pelvis and the trunk were similar between the two groups, their different timing patterns led to higher values in the elite group through impact. Due to its great mass, e.g. $\sim 70\%$ of body mass (Winter, 1990) and the positive influence of trunk rotation on horizontal shoulder velocity, it can be seen as the key feature of racquet speed generation in the present study. Data also showed that the pelvis and the trunk slowed down naturally. Consequently, there is no need to block certain segments, a fact already mentioned by Elliott et al. (2009).

Both groups increased internal rotation of the shoulder very late in the swing, which was similar to findings in the serve (Elliott et al., 1995; Fleisig et al.,

2003) and the forehand (Bahamonde and Knudson, 2003; Takahashi et al., 1996), but reached their peak values even after impact (Figure 4). These results demonstrate that both groups continued to increase the angular velocity of the shoulder through impact and shortly after. Although shoulder internal rotation can contribute up to 40% to the racquet speed at impact (Elliott et al., 1997), the peak values in our study must have been irrelevant in terms of racquet speed because of their occurrence after impact. The fact that maximum shoulder internal rotation velocity was similar for both groups, accentuates this explanation. Moreover, obtained data of shoulder angular velocities did not show a reduction in the down the line situation, which could have been assumed due to the need for more control (Elliott et al., 2009).

The later occurrence of maximum elbow angular velocities shows a proximal-to-distal kinematic chain in the elite group, which was not the case in the high performance players. Although not specifically studied, the high intraindividual variability and the high standard deviations in many of the analyzed variables and their timing clearly point out the individualism of each stroke and every player. For instance, some players make less use of shoulder internal rotation, thereby, making it absolutely necessary to force perfect trunk rotation in their forehand stroke. In addition, some variables will remain more constant and repeatable than others (Knudson, 1990).

Practical implications

Our findings suggest that for the improvement of the

forehand performance level, coaches and athletes should focus mainly on three things: proper 1) pelvis and 2) trunk rotation velocity and 3) their timing. A good rear leg drive will initiate pelvis rotation and, consequently, increase the separation angle, which will do its part in terms of storing elastic energy for subsequent rotations. In case of vigorous trunk angular velocity, the players will even step forward with their rear leg after impact. Overall this can be a model for technique training in the tennis forehand.

Conclusion

Comparing key mechanical features and their timing of forehand groundstrokes between ATP-professionals (elite) and high performance youth players was the main aim of the present study. The results indicate that the tendency towards higher horizontal shoulder and racquet velocities in the elite group were caused by significantly different timing patterns of maximum angular pelvis and trunk rotations. When comparing the cross court to the down the line situation, different results for maximum hip, racquet and separation angles, horizontal racquet speeds, and different timings of peak elbow velocities explain that both groups adapted their swings according to the respective condition. Results suggest that coaches should especially focus on proper pelvis and trunk rotation in order to improve the forehand technique of their players. In terms of strength and conditioning, coaches should keep the principle of kinematic affinity between tennis groundstroke techniques and strength training exercises in mind. Therefore, they need to find exercises that mimic tennis specific movements and involve the coordination of body segments.

Future studies with a higher number of professional players are needed to emphasize our findings and to be able to create a “perfect forehand stroke” model.

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Key points

- Different timing of maximum angular pelvis and trunk rotations separated the elite from the high performance players.
- The elite group tended to reach higher horizontal shoulder and racquet velocities than the high performance group.
- In addition to maximum angular velocities, maximum racquet, shoulder, and hip alignment angles were similar between groups.
- To improve the forehand performance level of their athletes, coaches should focus on proper pelvis and trunk rotation.

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