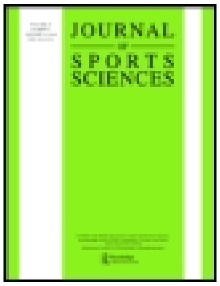

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Abstract

In tennis, a high ball velocity and a fast run toward the net are key features to successful performance of "serve-and-volley" players. For the serve, tennis players can use two techniques: the foot-up (FU) or foot-back (FB) technique. The aim of this study was to determine if the running time toward the net after the serve and the ball velocity (V_{ball}) vary between these two techniques. Moreover we analysed the angular momentum values of the trunk and of the arm holding the racquet. Fifteen expert tennis players performed six successful serve-and-volleys with both techniques. Running time to the net is significantly lower for FB, whereas V_{ball} is significantly higher for FU. Trunk and arm angular momentums about the transverse axis are significantly higher with FU before ball impact. A significant correlation ($r = 0.81$, $P < 0.001$) exists between changes in the maximal trunk angular momentum and in running time to the net between the two serve techniques. A significant correlation ($r = 0.84$, $P < 0.001$) also exists between changes in the maximal trunk angular momentum and in V_{ball} between the two serve techniques. According to these results, FB is the best technique for moving as quickly as possible to the net because of a lower trunk angular momentum.

Keywords: *tennis, biomechanics, kinematics, technique*

Introduction

In the tennis serve-and-volley, moving to the net as quickly as possible is crucial to impact the volley in an advantageous court location. Consequently, the running time toward the net after the serve is a key factor in an effective serve-and-volley performance (Crespo & Miley, 1999). For the serve, players can use two main serve techniques. According to Elliott and Wood (1983), some players bring the back foot up to the front foot prior to pushing backward and downward ("foot-up [FU] technique"), whereas the others leave the rear foot back during the early movement of the racquet and then swing this foot around and forward prior to impact ("foot-back [FB] technique"). Although Elliott and Wood (1983) described the influence of FU and FB techniques on ground reaction forces and kinematic parameters during the serve, their impact on the serve-and-volley performance is unknown. During Roland Garros 2007, the French Tennis Federation classified FU and FB according to game style of 99 professional players (Renoult, 2007). The results showed that a higher proportion of "serve-and-volley" players used FB compared to baseline players. As the "serve-and-volley" players tended to favour FB compared with those classified as "baseliners", one wonders if FB enhances the performance of "serve-and-volley" players. Consequently, to improve the understanding of high level "serve-and-volley", it is necessary to analyse the influence of the feet stance technique on its performance (running time to the net and ball velocity).

In tennis, the serve is a sequence of motions referred to as a "kinetic chain" (Elliott, Fleisig, Nicholls, & Escamilia, 2003) that begins with the lower limb action and is followed by rotations of the trunk and upper limb. This kinetic chain involves a transfer of linear and angular momentum from the legs to the trunk and then to the arm and the racquet (Bahamonde, 2000). As the starting point of the "kinetic chain", the legs play a major role in the serve, and their action necessarily affects its performance by influencing the linear and angular movements of the trunk and upper arm (Elliott & Wood, 1983; Girard, Micallef, & Millet, 2007).

Different authors have evaluated the characteristics of linear momentum for these serve techniques. Using FU allows a more powerful upward drive than using FB (Strandberg & Jones, 1981). This idea has

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been confirmed by other studies (Bahamonde & Knudson, 2001; Elliott & Wood, 1983), which recorded larger peak vertical ground reaction forces for FU than for FB. However, FU creates a greater horizontal braking force that limits the forward linear momentum of the body, which may hinder serve-and-volley players (Bahamonde & Knudson, 2001). Moreover, with FB, players are able to generate greater propulsive forces toward the net, thus generating more linear forward momentum, which may increase how fast a player can move toward the net (Bahamonde & Knudson, 2001; Elliott & Wood, 1983). These previous studies were mainly interested in translation movement of the serve, whereas the serve also implies whole-body and segmental rotations, that create angular momentum about longitudinal and transverse axes (Bahamonde, 2000).

The transverse angular momentum of the body about its centre of mass depends only on the magnitude of the ground reaction forces and on the location of the line of force action relative to the centre of mass (Zatsiorsky, 2002). Different studies have shown that these latter parameters vary according to the serve technique used (Bahamonde, 2000; Bahamonde & Knudson, 2001; Elliott & Wood, 1983). Indeed, it has been reported that FU causes higher vertical ground reaction force and larger horizontal braking force than FB (Bahamonde & Knudson, 2001; Elliott & Wood, 1983), which may enable greater angular momentum to be produced for FU (Bahamonde & Knudson, 2001). Moreover, FU produces a forward shift of the centre of mass from a position between the feet to a position in front of the front foot (Smith, 1979). The combination of higher vertical ground reaction force, larger horizontal braking force and the shift of the centre of mass during FU generates a greater off-centre impulse behind the centre of mass of the player (Bahamonde, 2000). This off-centre impulse would produce a greater forward angular momentum about the transverse axis with FU. On the other hand, FB generates vertical ground reaction force both on the front foot and the back foot (Girard, Eicher, Micallef, & Millet, 2010). This latter study emphasises the importance of the reaction force exerted by the front foot is at least as important as the rear foot. The ground reaction force exerted by the front foot tends to counteract the forward angular momentum created by the rear foot with FB.

During serve-and-volley, forward angular momentum of the tennis player's body has to be kept within strict limits to ensure postural stability and visual control of the ball and the opponent. Although forward angular momentum is necessary to accelerate linearly forward after the serve is completed, an excessive forward body rotation about the transverse axis with FU could increase the difficulty in quickly moving toward the net after the serve. Indeed, if the amount of forward angular momentum is larger at the instant of landing of the server with FU, the player needs to quickly reduce it to reach an amount of body rotation that enables him not only to maintain a dynamic balance but also to look at the ball direction and the opponent response. However, decreasing the forward angular momentum is not beneficial for the creation of high ball velocity.

Bahamonde (2000) has quantified and explained the evolution of angular momentum during the tennis serve. However, it is unknown whether the forward angular momentum created according to the serve technique (FU and FB) would differently affect the running time to the net and ball velocity. As a consequence, the primary aim of this work is to determine if the performance factors ball velocity (V_{ball}) and running time to the net vary according to the different serve techniques.

Methods

Participants

Fifteen expert tennis players (11 males and 4 females, age: 25 ± 6.1 years, height: 1.79 ± 0.07 m, body mass: 71.0 ± 7.4 kg, body mass index (BMI): 22.08 ± 1.71 $kg \cdot m^{-2}$), with an International Tennis Number of 2 or better (International Tennis Federation, 2009), participated voluntarily in this study. Nine participants were professional players holding an Association of Tennis Professionals (ATP) (88th, 298th, 797th, 972th, and 1192th) or Women's Tennis Association (WTA) ranking (27th, 34th, 40th, and 60th). The others were national level players. Of the 15 participants, 12 preferred the FU technique, whereas 3 had a preference for the FB, but all players were able to use both techniques. Before participation, the participants underwent a medical examination and were fully informed of the experimental procedures. Written consent was obtained for each player. The study respected all local laws for studies involving human participants and was approved by the Ethics Board of the University of Rennes 2.

Experimental protocol

Prior to filming, participants viewed a demonstration of the experimental procedure and both techniques (FU and FB) performed by a professional coach. They had all the time they needed to familiarise themselves with the testing environment and the landmarks set, as well as to test both techniques (FU and FB). After a warm-up of 10 minutes, each player performed six high-speed "flat" FU and six high-speed FB successful "serve-and-volley" movements from the right serve court to a 1.50×1.50 m target area bordering the T of the "deuce" serve box. At the completion of the serve, the players were asked to move as quickly as possible to the "split step box" in a 1.5-m square located in front of the serve line (Figure 1). When the player arrived at the box, he mimicked a volley as in match situation. The ability of the players to properly perform each technique was confirmed by a professional tennis coach. A 30-s rest period was allowed between trials. Mullineaux, Bartlett, and Bennett (2001) recommended that at least three trials must be considered in the derivation of accurate and representative movement kinematics.

In-situ motion capture

The experiment took place in the National Training Centre of the French Tennis Federation "Roland Garros" in an indoor tennis court. A Vicon MX-40 motion analysis system (Oxford Metrics Inc., Oxford, UK) was used to record the three-dimensional (3D) landmark trajectories to reconstruct the serve motions of each player. This system was composed of 12 high-resolution cameras (4 megapixels) operating at a nominal frame rate of 300 Hz, which were positioned as shown in Figure 1. Players were equipped with 38 retro-reflective markers placed on anatomical landmarks (Figure 2). Five additional landmarks were positioned on the racquet, and reflective tape was placed on the ball to determine the instants of ball toss and impact. Players wore tight shorts and no shirt to limit movement of the markers from their anatomical landmarks. After the capture, 3D coordinates of the landmarks were reconstructed with ViconIQ software (IQ, Vicon, Oxford, UK) with a residual error of less than 1 mm.

Performance parameters

To analyse the influence of the serve technique on subsequent movement toward the net, two critical performance parameters were evaluated: the running time to the net and the post-impact ball velocity (V_{ball}). The running time to the net is the time needed to reach the split step box. It starts at the first toe contact on the floor after the serve and ends when the centre of mass of the server crosses the serve line. V_{ball} was measured for each trial by using a radar (Stalker Professional Sports Radar, Plano, TX, accuracy: +/– 1mph, frequency: 34.7GHz, target acquisition time: 0.01 s) fixed on a 2.5-m high tripod, 2 m behind the players in the direction of the serve. The duration of the first foot-floor contact during the landing of the server was also measured.

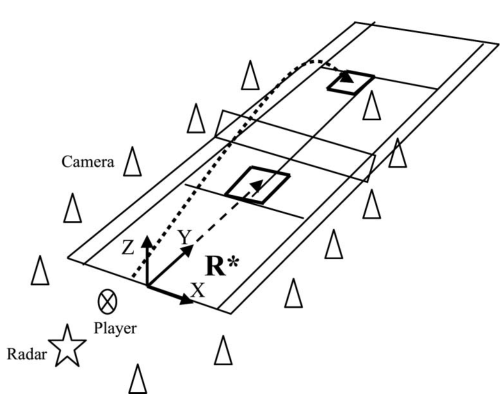

Figure 1. The filming set-up.

Kinetic variables

This study was focused on the transverse angular momentum of the trunk and of the arm that holds the racquet as the angular momentum of the body is primarily contained in these segments (Bahamonde, 2000). Moreover, these segments are the ones that most contribute to the racquet speed in the tennis serve (Elliott, Marshall, & Noffal, 1995; Gordon & Dapena, 2006; Sprigings, Marshall, Elliott, & Jennings, 1994). The angular momentum of any segment i about the transverse axis was calculated using the following equation:

$$L_i = m_i \cdot (r_i \times v_i) + I_i \cdot \omega_i \tag{1}$$

where L_i is the angular momentum of segment i, r_i is the vector from the centre of mass of the body to the

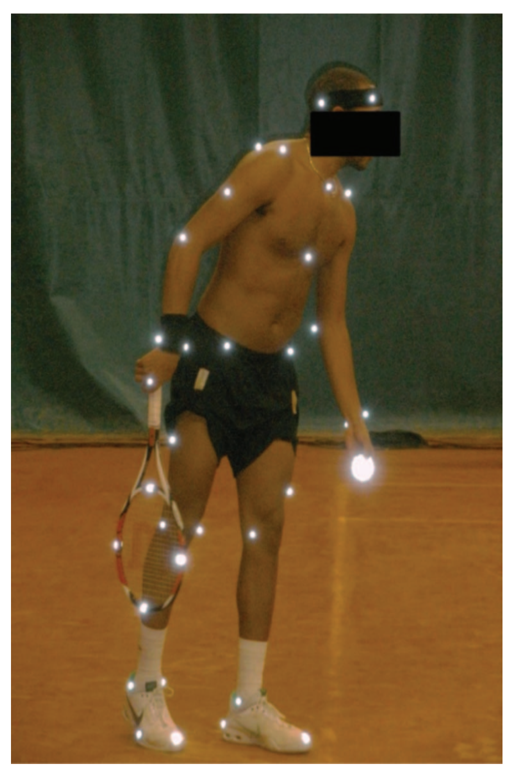

Figure 2. The marker positions.

centre of mass of segment i, m_i is the mass of segment i, v_i is the instantaneous velocity of the centre of mass of segment i relative to the centre of mass of the whole body, I_i is the moment of inertia of segment i about the transverse axis and ω_i is the angular velocity of segment i about the transverse axis. Forward trunk angular momentum means that the trunk performs a clockwise rotation about the transverse axis as viewed by an observer located to the right of the server.

Anthropometrical parameters were obtained from De Leva (1996), and all the parameters and variables were calculated using Matlab software 6.5 (Mathworks, Natick, Massachusetts, USA).

The serve was divided into the following main phases as described by Bahamonde (2000): ball toss, instant of maximal elbow flexion of the arm holding the racquet, instant when the racquet reached its lowest point, instant of maximal external rotation of the shoulder (racquet side), impact, and end of the serve (Figure 3). The end of the serve was defined as the instant of first toe contact with the floor when the server landed. The sprint was defined as the period of time between the instant of landing of the server and the instant when the server's centre of mass crossed the serve line. Ball toss and impact were determined by direct observation of the recorded data, and the times of the other events were calculated from the kinematic data.

To evaluate the influence of the body rotation about the transverse axis on running time to the net and V_{ball}, correlations between maximal values of trunk angular momentum and running time to the net and between maximal trunk angular momentum and V_{ball} were analysed. All these data (trunk angular momentum, running time to the net and V_{ball}) were expressed as percentages of the FU values relative to the FB ones.

To evaluate the sequence of motions of the trunk and of the segments holding the racquet, their angular momentum values about the transverse axis were computed for each of the stages of the serve.

Statistical analyses

Means and standard deviations (six trials for each player) were calculated for all variables. Paired T-tests (FU vs. FB) were used to evaluate the influence of the serve technique on V_{ball}, running time to the net, duration of the first foot-floor contact, trunk angular momentum and arm angular momentum. When the normality test failed, a Wilcoxon signed ranks test was used. Pearson correlation coefficients were used to assess the relationships between maximal trunk angular momentum and running time to the net and between maximal trunk angular momentum and V_{ball} during serve-and-volley performed with FU and FB (SigmaStat 3.1, Jandel Corporation, San Rafael, CA). The level of significance was established at $P < 0.05$. As recommended by Knudson (2009), effect size was calculated to document the size of the statistical effects observed and defined as small for $r > 0.1$, medium for $r > 0.3$, and large for $r > 0.5$ (Cohen, 1988).

Results

Performance parameters

The results of performance parameters for the "serve-and-volley" with both techniques are presented in Table I. V_{ball} was significantly higher ($P < 0.001$) with FU ($48.1 \pm 6.0\ \mathrm{m \cdot s^{-1}}$) compared

Table I. Performance parameters during "serve-and-volley" performed with FU and FB.

	FU	FB	P	Effect size
V_{ball} ($\mathrm{m \cdot s^{-1}}$)	48.1 ± 6.0	46.2 ± 6.8	$P < 0.001$	0.558
RTN (s)	1.56 ± 0.21	1.49 ± 0.22	$P < 0.001$	0.702
$D_{contact}$ (s)	0.31 ± 0.03	0.29 ± 0.04	$P < 0.001$	0.532

Values are mean $\pm$ s, $n = 15$. RTN: running time to the net, $D_{contact}$: duration of the first foot-floor contact.

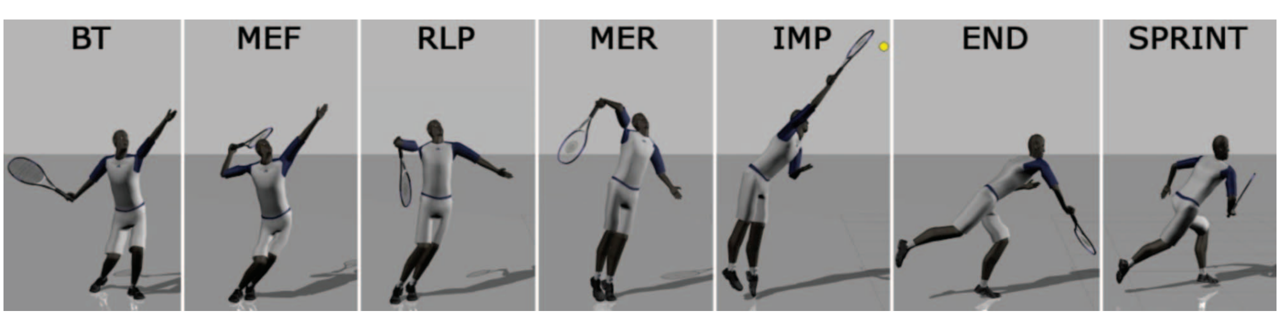

Figure 3. The main events of the "serve-and-volley".

with FB ($46.2 \pm 6.8\ \mathrm{m \cdot s^{-1}}$) and reported large effect size ($r = 0.558$). When statistically significant differences are observed between two conditions, obtaining a large effect size emphasises these findings. Players were significantly faster in running time to the net ($P < 0.001$) with FB (1.49 ± 0.22 s) compared with the FU (1.56 ± 0.21 s). A large effect size emphasises this result ($r = 0.702$). The duration of the first foot-floor contact at the reception of the serve was significantly longer ($P < 0.001$) with FU (0.31 ± 0.03 s) compared with FB (0.29 ± 0.04 s). A large effect size was calculated for this result ($r = 0.532$).

Kinetic variables

The maximum magnitude of trunk angular momentum about the transverse axis was significantly higher ($P < 0.001$) with FU ($-9.46 \pm 2.93\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$ compared with FB ($-8.38 \pm 2.37\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$).

Tables II and III present the average values of trunk and arm angular momentums during the various phases of the serve. From ball toss to maximal elbow flexion, no significant difference was recorded in the average values of trunk angular momentum with FU ($0.05 \pm 0.17\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$) and FB ($0.04 \pm 0.21\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$) ($P = 0.859$, $r = 0.019$). However, for the following stages of the serve-and-volley such as maximal elbow flexion–racket lowest point, racket lowest point–maximal external rotation, maximal external rotation–impact, impact–end of the serve, and sprint, FU generated greater trunk angular momentum than FB (Table II).

From maximal external rotation to impact, FU ($-13.85 \pm 3.06\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$) was characterised by higher forward arm angular momentum ($P < 0.001$) than FB ($-12.75 \pm 3.50\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$) and reported large effect size ($r = 0.615$). Between impact and end of the serve, forward arm angular momentum was significantly higher ($P < 0.05$) for FU ($-6.04 \pm 1.83\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$) than for FB ($-5.73 \pm 1.92\ \mathrm{kg \cdot m^2 \cdot s^{-1}}$) and reported small effect size ($r = 0.237$). For the other stages of serve-and-volley (ball toss–maximal elbow flexion, maximal elbow flexion–racket lowest point, racket lowest point–maximal external rotation, and sprint), results showed no significant difference for arm angular momentum between FU and FB.

Relationship between trunk angular momentum and running time to the net

The relationship between maximal trunk angular momentum about the transverse axis and running time to the net for both techniques is presented in Figure 4. A significant correlation ($r = 0.81$, $r^2 = 0.66$, $P < 0.001$) exists between increases in maximal trunk angular momentum and increases in running time to the net between the two serve techniques.

Relationship between trunk angular momentum and V_{ball}

The relationship between maximal trunk angular momentum about the transverse axis and V_{ball} for both techniques is presented in Figure 5. A significant correlation ($r = 0.84$, $r^2 = 0.71$, $P < 0.001$) exists between increases in maximal trunk angular momentum and increases in V_{ball} between the two serve techniques.

Evolutions of trunk and arm angular momentums

Typical evolutions of trunk and arm angular momentums about the transverse axis during the various

Table II. Average trunk angular momentum (L_{trunk}) about the transverse axis between events of the "serve-and-volley".

	L_{trunk} ($\mathrm{kg \cdot m^2 \cdot s^{-1}}$)			
Events	FU	FB	P	Effect size
BT – MEF	0.05 ± 0.17	0.04 ± 0.21	$P = 0.859$	0.019
MEF – RLP	-3.92 ± 1.62	-3.53 ± 1.11	$P = 0.004$	0.297
RLP – MER	-8.14 ± 2.59	-7.23 ± 2.02	$P < 0.001$	0.511
MER – IMP	-4.81 ± 1.87	-4.16 ± 1.61	$P < 0.001$	0.562
IMP – END	-1.89 ± 0.84	-1.65 ± 0.79	$P < 0.001$	0.422
SPRINT	0.84 ± 0.27	0.78 ± 0.23	$P = 0.027$	0.232

Positive values indicate counterclockwise (backward) angular momentum and negative values clockwise (forward) angular momentum viewed with the positive X-axis pointing toward the observer. Values are mean ± s, n=15. BT: ball toss, MEF: maximal elbow flexion, RLP: racket lowest point, MER: maximal external rotation of the shoulder, IMP: impact, END: end of the serve.

Table III. Average arm angular momentum (L_{arm}) about the transverse axis between events of the "serve-and-volley".

	L_{arm} ($\mathrm{kg \cdot m^2 \cdot s^{-1}}$)			
Events	FU	FB	P	Effect size
BT – MEF	-0.28 ± 0.34	-0.25 ± 0.42	$P = 0.952$	0.007
MEF – RLP	-2.02 ± 0.90	-1.98 ± 0.93	$P = 0.581$	0.059
RLP – MER	-9.89 ± 2.64	-9.53 ± 2.52	$P = 0.122$	0.163
MER – IMP	-13.85 ± 3.06	-12.75 ± 3.50	$P < 0.001$	0.615
IMP – END	-6.04 ± 1.83	-5.73 ± 1.92	$P = 0.024$	0.237
SPRINT	0.16 ± 0.25	0.16 ± 0.91	$P = 0.105$	0.171

Positive values indicate counterclockwise (backward) angular momentum and negative values clockwise (forward) angular momentum viewed with the positive X-axis pointing toward the observer. Values are mean ± s, n = 15. BT: ball toss, MEF: maximal elbow flexion, RLP: racket lowest point, MER: maximal external rotation of the shoulder, IMP: impact, END: end of the serve.

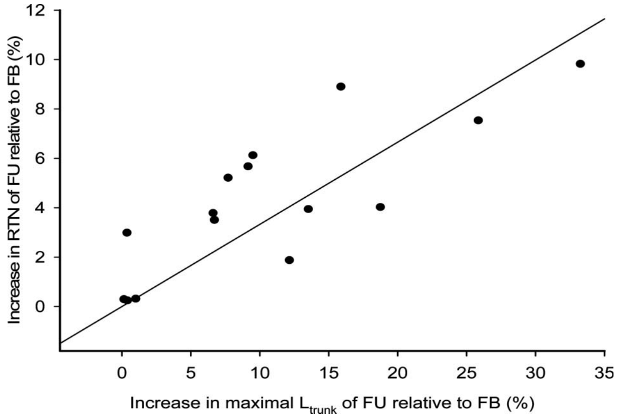

Figure 4. Relationship ($r = 0.81$, $P < 0.001$) between maximal changes in trunk angular momentum (L_{trunk}) about the transverse axis and changes in running time to the net (RTN) during "serve-and-volley" performed with FU and FB ($n = 15$). All these data are expressed as the percent increases in the FU values relative to the FB ones.

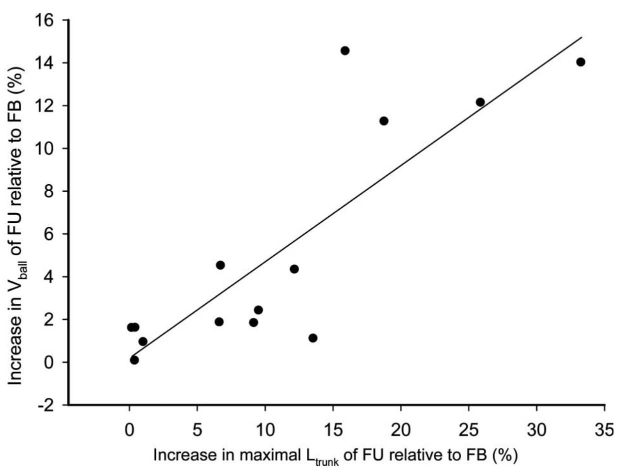

Figure 5. Relationship ($r = 0.84$, $P < 0.001$) between changes in maximal trunk angular momentum (L_{trunk}) about the transverse axis and changes in V_{ball} during "serve-and-volley" performed with FU and FB techniques ($n = 15$). All these data are expressed as the percent increases in the FU values relative to the FB ones.

phases of the "serve-and-volley" are presented in Figure 6.

Discussion

The primary aim of this work was to determine if the performance factors (V_{ball} and running time to the net) varied according to the different serve techniques.

Effect of serve technique on V_{ball}

The mean V_{ball} values measured for FU and FB (48.1 and 46.2 $m \cdot s^{-1}$, respectively; Table I) are in accordance with previous results in high-performance tennis players (Elliott et al., 2003; Tanabe & Ito, 2007). A significant relationship was observed

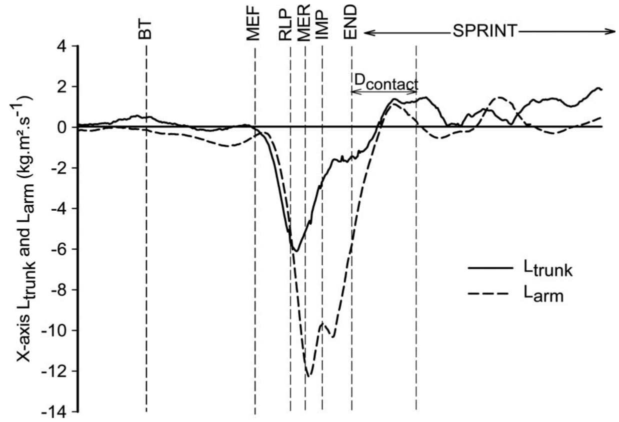

Figure 6. Typical evolution of trunk and arm angular momentums (L_{trunk} and L_{arm}) between the events of "serve-and-volley" about the transverse axis. Positive values indicate counterclockwise (backward) angular momentum and negative values clockwise (forward) angular momentum viewed with the positive transverse axis pointing toward the observer. BT: ball toss, MEF: instant of maximal elbow flexion, RLP: instant when the racquet reached its lowest point, MER: instant of maximal external rotation of the shoulder, IMP: impact, END: end of the serve, $D_{contact}$: the duration of the first foot-floor contact.

between changes in maximal trunk angular momentum and in V_{ball} (Figure 5). Players with the greatest increases in maximal trunk angular momentum for FU compared with FB are those with the greatest increases in V_{ball} for FU compared with FB. Elliott and Wood (1983) compared serve velocities obtained with FU and FB for expert tennis players and reported similar post-impact ball velocities (39.9 $m \cdot s^{-1}$ and 39.8 $m \cdot s^{-1}$, respectively, for FU and FB). Furthermore, Reid, Elliott, and Alderson (2008) reported no significant difference in pre-impact peak resultant racquet velocity between FU (43.6 $m \cdot s^{-1}$) and FB (42.6 $m \cdot s^{-1}$). Racquet and ball speeds were therefore reported in the literature to be independent of the serve technique. However, in the current study, it is interesting to notice that mean V_{ball} was significantly higher for FU than for FB ($P < 0.001$). Bahamonde and Knudson (2001) have shown that the FU generates more vertical ground reaction forces, and hypothesised that players would produce higher ball velocity. Our results seem to support this hypothesis but further experiments should be conducted to establish the relationship between angular momentum and ball velocity during the tennis serve. In the serve of expert tennis players, body segments have to be coordinated to produce a high ball speed (Elliott, 2003). The angular momentum created during the serve corresponds to a three-lever system comprising the trunk, the arm and the racquet (Bahamonde, 2000; Payne, 1978). Our results seem to support this theory. Indeed, between maximal external rotation and impact, the trunk lost most of its forward angular momentum. In contrast, the arm holding the racquet gained most of its forward angular momentum during the same stage of the serve (Table III and Figure 6).

Because the forward trunk angular momentum between racket lowest point and maximal external rotation is higher with FU than with FB ($P < 0.001$), one may consider that the higher arm angular momentum between maximal external rotation and impact with FU in comparison to FB ($P < 0.001$) was the result of a greater transfer of forward angular momentum from the trunk to the arm holding the racquet with FU. Sprigings et al. (1994), Elliott et al. (1995), and Tanabe and Ito (2007) have shown that the internal rotation of the upper arm, rotations about transverse axes of the upper arm, and hand flexion were the major contributors (approximately 50%) to the forward velocity of the racquet at impact. As a consequence, a possible explanation for the larger V_{ball} with FU is the creation of higher arm angular momentum before the impact, resulting from a higher transfer of forward angular momentum from the trunk.

Effect of serve technique on trunk angular momentum

From maximal elbow flexion, the values of trunk angular momentum were significantly higher for FU compared with those for FB. That result may be related to the vertical ground reaction force. Indeed, according to Payne (1978), the angular momentum developed during the tennis serve is the consequence of an off-centre impulse behind the centre of mass of the player that is generated by the vertical ground reaction force. Smith (1979) described that the ground reaction force received by the players, before the ball impact, induced a forward shift of the centre of mass from a position between the feet to a position over or in front of the front foot. As the centre of mass shifted forward, the players developed braking forces with the front foot. Bahamonde and Knudson (2001) reported that FU generated greater vertical ground reaction force and a larger braking force than FB. So the combination of greater vertical ground reaction force and greater braking force for FU could make the resultant of these two forces more off-centre relative to the centre of mass of the players than with FB (Bahamonde, 2000). Thereby, this phenomenon increases the forward trunk angular momentum about the transverse axis for the serve-and-volley for FU compared with FB.

Effect of serve technique on running time to the net and duration of the first foot-floor contact

This study shows that the type of serve used (FB or FU) has an influence on the running time to the net. Players ran faster toward the net when using FB (Table I). A mean difference of 70 ms in running time to the net between FU and FB provides an advantage for the players who wish to move quickly and play a volley from an appropriate court location. For instance, a return at 33.9 $m \cdot s^{-1}$, typical for professional players (Choppin, Goodwill, & Haake, 2011), would enable the server to be approximately 2.4 m closer to the net for their volley, thus greatly enhancing the likelihood of a successful volley.

Logically, therefore, a significant relationship was observed between changes in maximal trunk angular momentum and in running time to the net from FB to FU (Figure 4). Players with the greatest increases in maximal trunk angular momentum from FB to FU were those with the greatest increases in running time to the net. A greater forward rotation of the trunk is then associated with FU, which delays movement to the net. Indeed, it is interesting to notice that between the racket lowest point and the end of the serve, mean absolute values of trunk angular momentum were higher than the ones measured during the sprint, irrespective of the serve technique selected (Table II). As a consequence, to rush toward the net as fast as possible, one may argue that the "serve-and-volley" player must reduce his important forward rotation by slowing down and straightening up the trunk to control the body and to look at the ball during the landing phase. After impact, the time needed to counter trunk angular momentum and to ease running to the net is longer with FU than with FB because FU generates greater trunk angular momentum. By producing ground reaction forces, it is possible that the first foot-floor contact during the landing phase of the server participated in that regulation of trunk angular momentum (Figure 6). This phenomenon could explain the longer duration of the first foot-floor contact and running time to the net obtained with FU. Moreover, another argument could explain the significant difference of duration of the first foot-floor contact between FU and FB. Indeed, Elliott and Wood (1983) reported that FU was characterised by a higher height of ball impact and a greater vertical ground reaction force. Consequently, as the players pushed more upward when using FU, we can suppose that they needed more time to recover dynamic balance during the landing phase before running to the net.

Conclusion

In conclusion, the goal of this study was to analyse the influence of the FU and FB serve techniques on the performance parameters (V_{ball}, running time to the net) of the "serve-and-volley" and on trunk and arm angular momentums. FB has the advantage of decreasing running time to the net during the "serve-and-volley'', and of decreasing duration of the first foot-floor contact during the server's landing period. FU produces greater angular momentum, which is shifted from the trunk to the arm and then to the racquet. This phenomenon induces higher V_{ball}. Consequently, coaches should ask their players to use the serve technique that corresponds to their game style. For example, the baseliners should use FU because it produces a higher V_{ball}. On the contrary, as it allows faster running toward the net, FB seems to be better to improve the performance of ''serve-and-volley'' in professional and high-level players. Future study including the angular momentum of the arm-plus-racquet system is necessary. Moreover, measuring ground reaction forces would be interesting to better understand the relationships between ground reaction forces and ball velocity during ''serve-and-volley''.

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