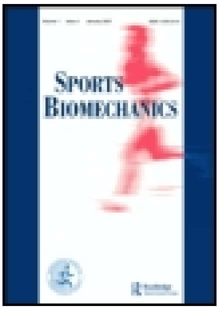

Sports Biomechanics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rspb20

Professional tennis players' serve: correlation between segmental angular momentums and ball velocity

Caroline Martin [a], Richard Kulpa [a], Paul Delamarche [a] & Benoit Bideau [a]

[a] M2S Laboratory, UFR APS, University of Rennes 2 - ENS Cachan, Rennes, France

Version of record first published: 12 Nov 2012.

Sports Biomechanics
2012, iFirst article, 1–13

Routledge
Taylor & Francis Group

Professional tennis players' serve: correlation between segmental angular momentums and ball velocity

CAROLINE MARTIN*, RICHARD KULPA, PAUL DELAMARCHE, & BENOIT BIDEAU

M2S Laboratory, UFR APS, University of Rennes 2 – ENS Cachan, Rennes, France

(*Received 29 August 2011*; *accepted 24 September 2012*)

Abstract
The purpose of the study was to identify the relationships between segmental angular momentum and ball velocity between the following events: ball toss, maximal elbow flexion (MEF), racket lowest point (RLP), maximal shoulder external rotation (MER), and ball impact (BI). Ten tennis players performed serves recorded with a real-time motion capture. Mean angular momentums of the trunk, upper arm, forearm, and the hand-racket were calculated. The anteroposterior axis angular momentum of the trunk was significantly related with ball velocity during the MEF–RLP, RLP–MER, and MER–BI phases. The strongest relationships between the transverse-axis angular momentums and ball velocity followed a proximal-to-distal timing sequence that allows the transfer of angular momentum from the trunk (MEF–RLP and RLP–MER phases) to the upper arm (RLP–MER phase), forearm (RLP–MER and MER–BI phases), and the hand-racket (MER–BI phase). Since sequence is crucial for ball velocity, players should increase angular momentums of the trunk during MEF–MER, upper arm during RLP–MER, forearm during RLP–BI, and the hand-racket during MER–BI.

Keywords: *Timing sequence, racket, ball impact, toss, elbow flexion, shoulder, external rotation*

Introduction

In the professional male game, the serve has been reported to be the most important stroke (Johnson et al., 2006). For professional players, the ability to produce high ball velocity seems to be the key element of successful play, because it puts the opponent under stress and may hinder its return. In tennis, the serve is a sequence of motions referred to as a 'kinetic chain' (Elliott et al., 2003) that begins with the lower limb action and is followed by rotations of the trunk and the upper limb. Consequently, joint and segmental rotation contributions to racket velocity in the serve were of great interest in the literature (Van Gheluwe & Hebbelinck, 1985; Sprigings et al., 1994; Elliott et al., 1995; Gordon & Dapena, 2006; Tanabe & Ito, 2007). The proficiency of these rotations through the kinetic chain involves a transfer of linear and angular momentum (Groppel, 1992) from the legs to the trunk and then to the arm and the racket (Bahamonde, 2000). Although the concept of angular momentum transfer is frequently reported to be critical in producing explosive serves

*Correspondence: Caroline Martin, M2S Laboratory, UFR APS, Rennes 2 University – ENS Cachan, Avenue Charles Tillon, 35044 Rennes, France, E-mail: caromartin@numericable.fr

ISSN 1476-3141 print/ISSN 1752-6116 online © 2012 Taylor & Francis
http://dx.doi.org/10.1080/14763141.2012.734321

(Groppel, 1992; Elliott, 2003, 2006; Girard et al., 2005, 2007; Knudson, 2007; Reid et al., 2008; Chow et al., 2009), few studies have studied angular momentum during the tennis serve (Bahamonde, 2000; Gordon & Dapena, 2004; Martin et al., 2012).

While Bahamonde (2000) described, quantified, and explained the evolution of angular momentum during the tennis serve about the three orthogonal axes (transverse, anteroposterior, and longitudinal) in five collegiate tennis players, no follow-up study has been reported relating ball velocity to changes in the angular momentum. The serve is often divided into meaningful phases between key elements in facilitating its analysis (Bahamonde, 2000; Reid et al., 2007, 2008): ball toss (BT), instant of maximal elbow flexion (MEF) of the racket-arm, instant when the racket head reaches its lowest point (racket lowest point, RLP), instant of maximal external rotation (MER) of the racket-arm shoulder, and impact. There is, however, a lack of knowledge about the importance of these temporal phases in relation to angular momentum and ball velocity.

The purposes of this study were: (1) to identify the relationships between segmental angular momentums and ball velocity in professional players; (2) to identify the key temporal phases during which these relationships were particularly strong. Understanding these relationships may provide tennis practitioners with instructional and training guidelines for improving their serve performance.

Methods

Participants

Ten professional tennis players (age = 25.1 ± 5.0 years; height = 1.87 ± 0.06 m; mass = 79.4 ± 7.4 kg) have voluntarily participated in this study. The players had a singles (17th, 88th, 118th, 147th, 287th, 522nd, and 921st) or doubles ATP ranking (35th, 48th, and 210th). Prior to participation, the participants underwent a medical examination and were fully informed of the experimental procedures. Written consent was obtained from each player. The study respected all local laws for studies involving human subjects and was approved by the Ethics Board of the University of Rennes 2.

Experimental protocol

Participants were given as much time as needed to familiarize themselves with the testing environment and the attached markers. After a 10-min warm-up, each player was invited to perform successful 'flat' serves from the right service court to a 1.50 × 1.50 m target area bordering the T of the 'deuce' service box (Figure 1). A 30-s rest period was allowed between trials. Five trials were collected for each player following the recommendation of Mullineaux et al. (2001) to derive accurate and represent movement kinematics and kinetics.

In situ *motion capture*

The experiment took place in an indoor tennis court during 'Open de Moselle' ATP professional tournament held in Metz, France. Players were equipped with 38 retro-reflective markers placed on select anatomical landmarks (Figure 2). Five additional landmarks were positioned on the racket. Participants used their own racket during motion capture. A 12-camera (four megapixels; 300 Hz) Vicon MX-40 motion capture system (Oxford Metrics, Inc., Oxford, UK) was used to record the three-dimensional marker trajectories (Figure 1). The recorded trajectories were then used to reconstruct the motion of

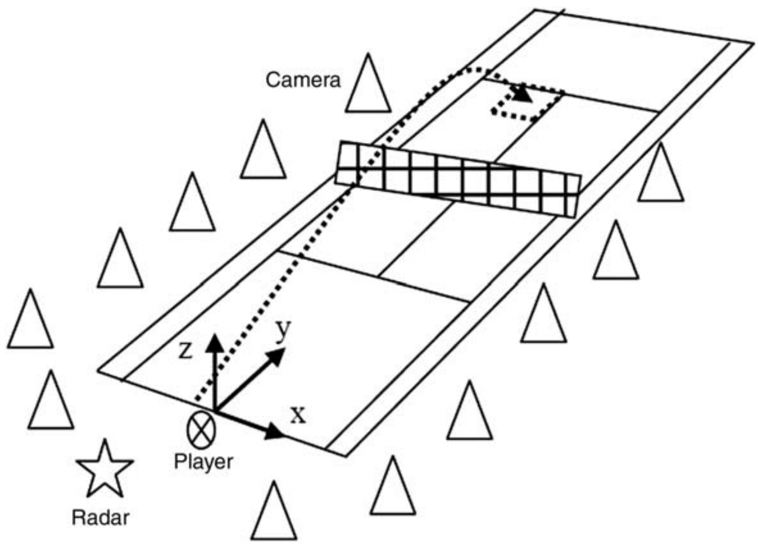

Figure 1. The filming set-up.

each player expressed in a right-handed inertial reference frame the origin of which is located at the centre of the baseline. The x-axis was parallel to the baseline with the y-axis pointing forward and z-axis being vertically upward (Figure 1).

Post-impact ball velocity

Post-impact ball velocity was measured using a radar gun (Stalker Professional Sports Radar, Plano, TX, USA; accuracy = ± 1 mph; frequency = 34.7 GHz; target acquisition time = 0.01 s) fixed on a 2.5 m height tripod located at 2 m behind the players with the axis aligned in the direction of the serve.

Phases of the serve

The serve was divided into four meaningful phases between the five following events: BT, instant of MEF of the racket arm, instant when the racket reached its RLP, instant of MER of the racket-arm shoulder, and ball impact (BI). BT and BI were determined by direct observation of the recorded data and the times of the other events were calculated from kinematic data (Figure 3).

Angular momentum

To evaluate the relationships between segmental angular momentum and ball velocity, mean angular momentums of the trunk and the dominant upper limb segments (upper arm, forearm, and hand-racket) about the transverse axis (x-axis of the inertial reference frame parallel to the baseline; also called the somersault axis by tennis coaches) and the anteroposterior axis (y-axis of the inertial reference frame normal to the baseline and pointing towards the net; shoulder-over-shoulder axis) (Figure 1): only the segmental angular momentums about these two axes were used because the longitudinal angular

Figure 2. The markers position.

momentums have been reported to be the smallest among the components and also highly variable among the players (Bahamonde, 2000). It was assumed that the hand and the racket rotated together as a perfectly rigid segment (Gordon & Dapena, 2006).

The angular momentum of a segment (i) was calculated using the following equation:

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

where L_i is the angular momentum of the segment, r_i is the relative position of the centre of mass of the segment to the centre of mass of the body, m_i is the mass of segment, v_i is the relative velocity of the centre of mass of segment to the centre of mass of the body, I_i is the inertia tensor of segment, and ω_i is the angular velocity of the segment. The transverse and the anteroposterior components of the angular momentum were used in the analysis. The segmental angular momentum values presented in this study are the mean values of the individual phases of the serve.

Anthropometrical parameters were taken from De Leva (1996) and all parameters and variables were calculated by a custom-made programme written in Matlab 6.5 (Mathworks, Natick, MA, USA). Moment of inertia of the racket about its transverse axis was computed using the parallel axis theorem and published racket swing weight data (USRSA, 2010). Racket moment of inertia about the long axis was calculated as recommended by Brody (1985)

$$\text{moment of inertia}\ (\text{kg}\cdot\text{m}^2) = \frac{\text{mass} \times \text{head width}}{17.75}. \tag{2}$$

Racket moment of inertia about its normal axis was the sum of the racket's other two principal moments of inertia (transverse and long; Brody, 1985; Table I; Figure 4).

Statistical analyses

M and *SD*s (five trials for each player) were calculated for all variables. Pearson's correlation coefficients ($\alpha = 0.05$) were used to assess the relationships between segmental angular momentums and ball velocity (SigmaStat 3.1, Jandel Corporation, San Rafael, CA, USA). Only the highest significant relationships between segmental angular momentums and ball velocity (i.e. $r > 0.70$ and $p < 0.001$) were considered to be meaningful and were discussed in this study.

Table I. Racket parameters used in the study.

Players	m (kg)	I_T (kg·m^2)	I_A (kg·m^2)	I_L (kg·m^2)
1	0.345	0.0124	0.0138	0.00135
2	0.360	0.0128	0.0141	0.00135
3	0.335	0.0154	0.0168	0.00135
4	0.340	0.0144	0.0156	0.00120
5	0.368	0.0167	0.0181	0.00140
6 and 7	0.340	0.0160	0.0173	0.00133
8, 9, and 10	0.365	0.0138	0.0151	0.00135

Notes: m, mass of the racket; I_T, moment of inertia of the racket about an axis passing through the centre of mass of the racket in the plane of the racket face (transverse); I_A, moment of inertia of the racket about an axis passing through the centre of mass of the racket perpendicular to the racket face (anteroposterior); I_L, moment of inertia of the racket about an axis passing through the centre of mass of the racket along the length of the racket (longitudinal).

Figure 3. The main events of the serve.

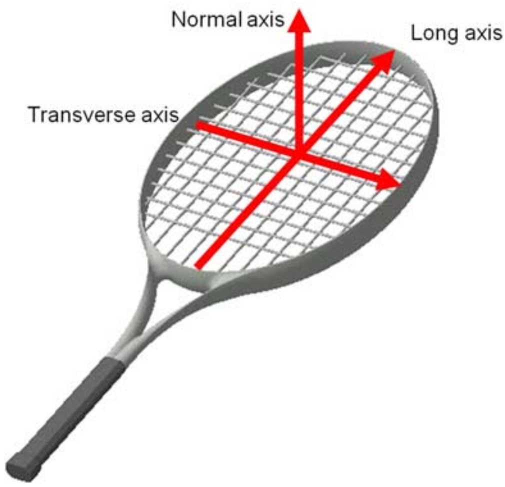

Figure 4. The axes of the racket.

Results

Segmental angular momentums about the transverse axis

Significant correlations ($p < 0.05$) existed between mean transverse axis trunk angular momentum values and ball velocity for the following serve phases: MEF–RLP, RLP–MER, and MER–BI (Table II). The upper arm revealed significant correlations between the angular momentum and ball velocity during the MEF–RLP, RLP–MER, and MER–BI phases, whereas the forearm did in all phases. The hand-racket segment also showed significant correlations in all but the MEF–RLP phase (Table II). Strong correlations between the transverse axis segmental angular momentums and ball velocity ($r > 0.70$ and $p < 0.001$) were observed in the MEF–RLP and RLP–MER phases for the trunk, in the RLP–MER phase for the upper arm, in the RLP–MER and MER–BI phases for the forearm, and in the MER–BI phase for the hand-racket (Table II).

Segmental angular momentums about the anteroposterior axis

The trunk segment was characterized by significant correlations between the anteroposterior axis angular momentum and ball velocity for the MEF–RLP, RLP–MER and MER–BI phases. The upper arm also revealed significant correlations for the RLP–MER and MER–BI phases. No significant correlation was observed in the forearm angular momentum. The hand-racket segment showed significant correlation for the LB–MEF phase.

Table II. Mean transverse axis segmental angular momentums of the serve phases and their correlations with ball velocity ($n = 0$ in kg·m^2/s).

	BT–MEF			MEF–RLP			RLP–MER			MER–BI		
	M ± *SD*	*r*	*p*	*M* ± *SD*	*r*	*p*	*M* ± *SD*	*r*	*p*	*M* ± *SD*	*r*	*p*
Trunk	0.0 ± 0.4	-0.13	0.392	-5.7 ± 3.3*	-0.70	<0.001	-7.7 ± 1.9*	-0.78	<0.001	3.8 ± 1.0	-0.63	<0.001
Upper arm	0.0 ± 0.1	-0.08	0.601	-2.4 ± 1.3	-0.62	<0.001	-6.3 ± 1.4*	-0.80	<0.001	-5.7 ± 1.1	-0.66	<0.001
Forearm	-0.2 ± 0.1	-0.38	0.009	-1.9 ± 0.9	-0.67	<0.001	-5.2 ± 1.2*	-0.78	<0.001	-7.9 ± 1.3*	-0.94	<0.001
Hand-racket	-0.6 ± 0.4	-0.39	0.008	-0.3 ± 0.6	-0.18	0.238	-2.6 ± 0.9	-0.53	<0.001	-11.4 ± 1.6*	-0.94	<0.001

Notes: Positive values indicate counterclockwise (forward) angular momentum and negative values clockwise (backward) angular momentum viewed with the positive transverse axis pointing towards the observer. BT, ball toss; MEF, instant of maximal elbow flexion; RLP, instant when the racket reached its lowest point; MER, instant of maximal external rotation of the shoulder; BI, ball impact. * The highest significant relationships between segmental angular momentums and ball velocity (i.e. $r > 0.70$ and $p < 0.001$).

Strong correlations ($r > 0.70$ and $p < 0.001$) between the anteroposterior axis segmental angular momentums and ball velocity were observed in the RLP–MER and MER–BI phases for the trunk.

Discussion and implications

The results of this study indicate that from MEF to BI, the players with the highest values of upper body segmental angular momentums about the transverse axis are those with the highest ball velocity. As a consequence, it seems that the ability of a player to produce high upper body segmental angular momentum values about the transverse axis during the serve increases ball velocity. To provide a more accurate analysis of this global result, it is necessary to consider individual relationships between segmental angular momentums and ball velocity during the different phases of the serve.

Relationships between angular momentum of the trunk and ball velocity

The most important findings of this study were the significant correlations between mean trunk angular momentum values and ball velocity about the transverse axis (Table II) and about the anteroposterior axis (Table III) during the MEF–RLP, RLP–MER, and MER–BI phases. Although it has been reported that the transverse rotation of the trunk produces a moderate contribution to the impact velocity of the racket (between 7.4% and 9.7%) by producing a mean velocity of 2.0–3.0 m/s for the shoulder (Van Gheluwe & Hebbelinck, 1985; Sprigings et al., 1994; Elliott et al., 1995), our results underline the obvious positive relation between trunk rotation and ball velocity in overhead movements. In baseball for instance, trunk forward tilt angle and angular velocity at the instant of ball release are of higher magnitude for higher velocity throwers (Matsuo et al., 2001).

Different arguments could explain the importance of forward angular momentum of the trunk. Indeed, since the shoulder is basically the endpoint of the trunk, trunk rotation influences the forward movement of the shoulder in a positive way, thereby increasing the speed of the racket from the instant of MEF. In addition, in overhead movements, the important contribution of the trunk to ball velocity has been emphasized since its acceleration has been associated with an explosive contraction of the internal rotators of an abducted shoulder (Pappas et al., 1985; Winge et al., 1989). This association between the trunk and the dominant shoulder seems crucial for increasing ball velocity since it has been shown that the shoulder internal rotation produces the greatest contribution to racket velocity (Sprigings et al., 1994; Elliott et al., 1995; Gordon & Dapena, 2006). Moreover, it is important to consider the trunk as a major link in the kinetic chain for the transfer of angular momentum from the legs to the upper limb (Bahamonde, 2000; Chow et al., 2009). Indeed, a segmental rotation may contribute marginally to the velocity of the racket at impact, but it may cause an essential indirect benefit by storing and then transferring angular momentum to the more distal links. As a consequence, coaches should encourage players to produce forward trunk angular momentum values as high as possible between MEF and MER to create favourable conditions for high ball velocity.

For the MEF–RLP, RLP–MER, and MER–BI phases, there were significant correlations between the trunk angular momentum values and ball velocity about the anteroposterior axis (Table III). In other words, the more the players produce negative trunk angular momentum about the anteroposterior axis between MEF and BI, the higher the ball velocity will be. These strong relationships confirm the results of Bahamonde (2000) suggesting that the rotation of the trunk about the anteroposterior axis differentiates players with the highest ball

Table III. Mean anteroposterior axis segmental angular momentums of the serve phases and their correlations with ball velocity ($n = 10$ in kg·m^2/s).

	BT–MEF			MEF–RLP			RLP–MER			MER–BI		
	M ± *SD*	*r*	*p*	*M* ± *SD*	*r*	*p*	*M* ± *SD*	*r*	*p*	*M* ± *SD*	*r*	*p*
Trunk	-0.8 ± 0.4	0.06	0.67	-1.4 ± 1.3	-0.60	<0.001	-2.0 ± 1.1*	-0.72	<0.001	-1.6 ± 0.9*	-0.71	<0.001
Upper arm	-0.2 ± 0.1	0.32	0.03	1.1 ± 0.6	0.06	0.69	0.2 ± 0.9	-0.47	<0.001	-0.3 ± 1.0	-0.60	<0.001
Forearm	0.0 ± 0.2	0.27	0.07	1.0 ± 0.6	0.10	0.49	0.8 ± 0.9	-0.34	0.02	1.4 ± 0.9	-0.28	0.06
Hand-racket	-0.2 ± 0.4	0.66	<0.001	0.1 ± 0.8	0.28	0.06	1.9 ± 0.7	-0.04	0.78	1.8 ± 1.3	-0.30	0.04

Notes: Positive values indicate counterclockwise angular momentum and negative values clockwise angular momentum viewed with the positive anteroposterior axis pointing towards the observer. BT, ball toss; MEF, instant of maximal elbow flexion; RLP, instant when the racket reached its lowest point; MER, instant of maximal external rotation of the shoulder; BI, ball impact. * The highest significant relationships between segmental angular momentums and ball velocity (i.e. $r > 0.70$ and $p < 0.001$).

speeds from players with the lowest ball speeds. In the same way, Chow et al. (2009) reported that right-handed advanced players had significantly greater left lateral flexion than the advanced intermediate players during the tennis serve. As a consequence, to maximize ball velocity, players would benefit from a coaching of the anteroposterior rotation of the trunk. First, the positive trunk angular momentum about the anteroposterior axis increases the downward rotation of the racket during the back loop. Then, the negative trunk angular momentum about the same axis elevates the dominant shoulder and lowers the opposite arm and therefore allows the player to reach a higher impact height. Moreover, it is well known that the distance over which racket speed can be developed is critical in producing explosive strokes (Elliott, 2003). Finally, Elliott (2006) suggested that the anteroposterior rotation of the trunk enables internal rotation of the upper arm at the shoulder to play an important role in the serve action.

Relationships between angular momentum of the upper arm and ball velocity

The transverse axis angular momentum of the upper arm was significantly correlated to ball velocity for the MEF–RLP, RLP–MER, and MER–BI phases, whereas the anteroposterior component was in the last two phases (RLP–MER and MER–BI). These results are in accordance with previous findings that showed a contribution of 6.4–12.9% of the transverse and anteroposterior rotations of the upper arm to the speed of the racket in the final part of the serve (Elliott et al., 1995; Gordon & Dapena, 2006; Tanabe and Ito, 2007). Moreover, Cohen et al. (1994) found a significant correlation between increased dominant shoulder flexion and serve velocity in competitive tennis players. In baseball, it has been reported that improper shoulder abduction was correlated to lower ball velocity (Matsuo et al., 2002). Transverse and anteroposterior upper arm rotations are important factors to increase ball velocity by influencing forward linear velocity of the elbow. In addition, transverse and anteroposterior upper arm rotations participate in elevating the shoulder until a ‘fixed position’ in space. Once the shoulder becomes fixed in space, the segments of the upper limb are free to rotate about the shoulder joint with an increase of angular velocity over time (Elliott et al., 1986; Bahamonde, 2000).

Relationships between angular momentum of the forearm and ball velocity

The transverse axis angular momentum of the forearm was significantly correlated to ball velocity in all four phases of the serve. The larger elbow extension angular velocity ($1510 \pm 310°/s$) for professional tennis players (Fleisig et al., 2003) than for amateur players ($1230 \pm 180°/s$) (Elliott et al., 1995) reflects the importance of that segmental rotation. Indeed, a greater angular momentum of the forearm about the transverse axis increases the forward linear velocity of the wrist and is thus important for accelerating the racket and, therefore, the ball. Relationships between serve velocity and elbow extension torque production in tennis players also have been reported (Ellenbecker, 1991; Cohen et al., 1994). As mentioned by Gordon and Dapena (2006), after approximately RLP, there is a rapid increase in the contribution of elbow extension to the speed of the racket. Before BI, the contribution of elbow extension to racket speed has been reported to be quite large (13.5 ± 3.6 m/s) in intercollegiate tennis players. Tanabe and Ito (2007) reported a small contribution ($3.2 \pm 6.0\%$) for the elbow extension to horizontal racket head velocity at BI. Surprisingly, however, Elliott et al. (1995) found that forearm extension played a negative role (-14.4%) in the forward velocity of the centre of the racket at impact. These discrepancies appear to be the results of differences in the level of players tested and in the method used to evaluate contributions of segmental rotations to racket speed in the tennis serve, as explained by Gordon and Dapena (2006). Indeed, Elliott et al. (1995) and Tanabe and Ito (2007) identified the contributions of segment rotations to the speed of the racket head at the instant of impact, while Gordon and Dapena (2006) examined these contributions to the velocity of the racket through the total duration of the tennis serve. In this study, we investigated the relationships between the changes of segmental angular momentums and ball velocity through all the phases of the serve.

Relationships between angular momentum of hand-racket and ball velocity

The transverse axis angular momentum of the hand-racket was significantly correlated to ball velocity for the BT–MEF, RLP–MER, and MER–BI. These results highlight the main influence of hand-racket rotation in the development of ball velocity. During the early backswing (BT–MEF), it has been shown that one of the main contributors to the racket speed is wrist extension (Gordon & Dapena, 2006). Our findings are in accordance with those reported in previous studies: between RLP and BI, the contribution of wrist flexion increased up to 26–31.7% of the racket speed before impact (Sprigings et al., 1994; Elliott et al., 1995; Gordon & Dapena, 2006; Tanabe & Ito, 2007). One study even observed a contribution of 51–75% for the hand rotation to the final velocity of the racket (Van Gheluwe & Hebbelinck, 1985). The transverse hand rotation is very important for ball velocity at the end of the forward swing since wrist flexion allows the players to increase the angular velocity of their racket from 1432.5 to 1570°/s just before impact (Elliott & Wood, 1983).

Proximal-to-distal segmental sequencing and temporal key phases of the serve

In sport movements, proximal-to-distal sequencing has been illustrated by examining the linear speeds of segment end-points, joint angular velocities, segment angular velocities, or resultant joint moments (Putnam, 1993). By investigating the strongest significant correlations between the segmental angular momentums and ball velocity, our findings confirm the importance of proximal-to-distal sequencing about the transverse axis (Table III) reported in the literature for throwing skills (Putnam, 1993) and for the two-dimensional analysis of the tennis serve (Elliott et al., 1986). This proximal-to-distal sequence between MEF and BI allows the player to transfer angular momentum from the trunk (MEF–RLP and RLP–MER) to the hand-racket (MER–BI phase) by flowing through the upper arm (RLP–MER) and the forearm (RLP–MER and MER–BI). Since sequence of segmental rotation about the transverse axis appears to be crucial for developing high ball velocity, players should mainly focus on increasing angular momentum of the trunk from MEF to MER, upper arm from RLP to MER, forearm from RLP to BI, and the hand-racket from MER to BI. Coaches and players should consider both the magnitude and timing of segmental angular momentum for increasing ball velocity.

Conclusion

The purposes of this study were (1) to define the relationships between upper body segmental angular momentum and ball velocity in professional tennis players, and (2) to identify the key temporal phases during which these relationships are particularly strong. Significant correlations were found between mean angular momentum of the trunk and ball velocity about the transverse and anteroposterior axes for the MEF–RLP, RLP–MER, and MER–BI phases. These results underline positive influence of trunk rotations to producing high ball velocities. The strongest significant relationships between segmental angular momentums about the transverse axis and ball velocity followed a proximal-to-distal timing sequence: in the MEF–RLP and RLP–MER phases for the trunk, in the RLP–MER phase for the upper arm, in the RLP–MER and MER–BI phases for the forearm, and in the MER–BI phase for the hand-racket. By identifying and highlighting the key temporal phases in terms of angular momentum–ball velocity relationship, the current study should help coaches to improve the serve performance of their players.

The serve in tennis can be seen as a complex coordinated movement that involves the development and the transfer of angular momentum to reach high ball velocity. Further research on tennis serve is needed to quantify and investigate the relationships between segmental angular momentum transfer and ball velocity.

Acknowledgements

The authors would like to thank the French Tennis Federation and Julien Boutter for their help in completing the study. The authors would also like to thank the players for their participation and cooperation.

References

Bahamonde, R. E. (2000). Changes in angular momentum during the tennis serve. *Journal of Sports Sciences*, *18*, 579–592.

Brody, H. (1985). The moment of inertia of a tennis racket. *The Physics Teacher*, *23*, 213–216.

Chow, J. W., Park, S. A., & Tillman, M. D. (2009). Lower trunk kinematics and muscle activity during different types of tennis serves. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*, *1*, 1–24.

Cohen, D. B., Mont, M. A., Campbell, K. R., Vogelstein, B. N., & Loewy, J. W. (1994). Upper extremity physical factors affecting tennis serve velocity. *The American Journal of Sports Medicine*, *22*, 746–750.

De Leva, P. (1996). Joint center longitudinal positions computed from a selected subset of Chandler's data. *Journal of Biomechanics*, *29*, 1231–1233.

Ellenbecker, T. S. (1991). A total arm strength isokinetic profile of highly skilled tennis players. *Isokinetic Exercise Science*, *1*, 9–21.

Elliott, B. (2003). Developing racquet velocity. In B. Elliott, M. Reid, and M. Crespo (Eds.), *Biomechanics of advanced tennis* (pp. 31–48). London: ITF Ltd.

Elliott, B. (2006). Biomechanics and tennis. *British Journal of Sports Medicine*, *40*, 392–396.

Elliott, B., Fleisig, G., Nicholls, R., & Escamilia, R. (2003). Technique effects on upper limb loading in the tennis serve. *Journal of Science and Medicine in Sport*, *6*, 76–87.

Elliott, B., Marsh, T., & Blanksby, B. (1986). A three dimensional cinematographic analysis of the tennis serve. *International Journal of Sport Biomechanics*, *2*, 260–271.

Elliott, B., Marshall, R., & Noffal, G. (1995). Contributions of upper limb segment rotations during the power serve in tennis. *Journal of Applied Biomechanics*, *11*, 433–442.

Elliott, B., & Wood, G. (1983). The biomechanics of the foot-up and foot-back tennis service techniques. *The Australian Journal of Sports Sciences*, *3*, 3–6.

Fleisig, G., Nicholls, R., Elliott, B., & Escamilla, R. (2003). Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomechanics*, *2*, 51–64.

Girard, O., Micallef, J. P., & Millet, G. (2005). Lower-limb activity during the power serve in tennis: Effects of performance level. *Medicine and Science in Sports and Exercise*, *37*, 1021–1029.

Girard, O., Micallef, J. P., & Millet, G. (2007). Influence of restricted knee motion during the flat first serve in tennis. *Journal of Strength and Conditioning Research*, *21*, 950–957.

Gordon, B. J., & Dapena, J. (2004). *Angular momentum transfer during a power tennis serve*. Poster presentation at 28th annual convention ASB. Portland.

Gordon, B. J., & Dapena, J. (2006). Contributions of joint rotations to racquet speed in the tennis serve. *Journal of Sports Sciences*, *24*, 31–49.

Groppel, J. L. (1992). *High tech tennis*. Champaign, IL: Leisure Press.

Johnson, C. D., McHugh, M. P., Wood, T., & Kibler, B. (2006). Performance demands of professional male tennis players. *British Journal of Sports Medicine*, *40*, 696–699.
Knudson, D. (2007). Qualitative biomechanical principles for application in coaching. *Sports Biomechanics*, *6*, 109–118.
Martin, C., Bideau, B., Nicolas, G., Delamarche, P., & Kulpa, R. (2012). How does the tennis serve influence the serve-and-volley? *Journal of Sports Sciences*, *30*, 1149–1156.
Matsuo, T., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., & Andrews, J. R. (2001). Comparison of kinematic and temporal parameters between different pitch velocity groups. *Journal of Applied Biomechanics*, *17*, 1–13.
Matsuo, T., Matsumoto, T., Mochizuki, Y., Takada, Y., & Saito, K. (2002). Optimal shoulder abduction angles during baseball pitching from maximal wrist and minimal kinetics viewpoints. *Journal of Applied Biomechanics*, *17*, 75–84.
Mullineaux, D. R., Bartlett, R. M., & Bennett, S. (2001). Research design and statistics in biomechanics and motor control. *Journal of Sports Sciences*, *19*, 739–760.
Pappas, A. M., Zawacki, R. M., & Sullivan, T. J. (1985). Biomechanics of baseball pitching: A preliminary report. *The American Journal of Sports Medicine*, *13*, 40–46.
Putnam, C. (1993). Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *Journal of Biomechanics*, *26*, 125–135.
Reid, M., Elliott, B., & Alderson, J. (2007). Shoulder joint loading in the high performance flat and kick tennis serves. *British Journal of Sports Medicine*, *41*, 884–889.
Reid, M., Elliott, B., & Alderson, J. (2008). Lower-limb coordination and shoulder joint mechanics in the tennis serve. *Medicine and Science in Sports and Exercise*, *40*, 308–315.
Sprigings, E., Marshall, R., Elliott, B., & Jennings, L. (1994). A three dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racket-head speed. *Journal of Biomechanics*, *27*, 245–254.
Tanabe, S., & Ito, A. (2007). A three dimensional analysis of the contributions of upper limb joint movements to horizontal racket head velocity at ball impact during tennis serving. *Sports Biomechanics*, *6*, 418–433.
USRSA. (2010). *Racquet Sports Industry Magazine, 38*, 29–32.
Van Gheluwe, B., & Hebbelinck, M. (1985). Kinematics of the service movement in tennis: A three-dimensional cinematographical approach. In D. Winter, R. Norman, R. Wells, K. Hayes, and A. Patla (Eds.), *Biomechanics IX-B* (pp. 521–525). Champaign, IL: Human Kinetics.
Winge, S., Joergensen, V., & Nielsen, A. L. (1989). Epidemiology of injuries in Danish championship tennis. *International Journal of Sports Medicine*, *18*, 366–375.